VOLUME XXX NUMBER 1

THE PHYSICAL REVIEW

A JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS

CONDUCTED

WITH THE CO-OPERATION OF THE

AMERICAN PHYSICAL SOCIETY

BY

EDWARD L. NICHOLS

ERNEST MERRITT and FREDERICK BEDELL

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JANUARY, 1910

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THE

PHYSICAL REVIEW.

THE VARIATION OF THE HALL EFFECT IN METALS WITH CHANGE OF TEMPERATURE.

By Alpheus W. Smith.

Introduction.

In 1879 Professor Hall[1] discovered that when a thin sheet of metal which is carrying a current of electricity is brought into a magnetic field, so that the lines of force are perpendicular to the plane of the plate, there is set up in the plate an electromotive force which is at right angles to that which is driving the current. This effect which is known as the Hall effect, has been the subject of a large amount of experimental and theoretical work. In later years several other phenomena which are related to it have been discovered and studied by other investigators. A fairly complete list of titles of articles on the Hall effect and allied phenomena has been prepared by McKay[2] and a review of the more important papers dealing with these phenomena has been recently published by Zahn.[3] It does not seem desirable at this time to review again at any length the work which has been done in this region.

One phase of the subject which seems to have been inadequately handled either theoretically or experimentally is the variation of the Hall effect with change of temperature. So far as the author is aware the temperature coefficient of this effect is known in the case of the non-magnetic metals only for bismuth, antimony and tellurium. The temperature coefficient of the effect in bismuth and antimony

[1] Amer. Jour. Math. (2), pp. 287–292, 1879.
[2] Proc. Amer. Acad. of Arts and Sci. (41), pp. 385–395, 1906.
[3] Jahr. der Radioaktivität und Elektronik (5), p. 166, 1908.

has been studied between — 186° C. and the melting point of the metal. The effect is found to decrease with rising temperature and within the error of observation to vanish at the melting point of the metal in question. It seems that the presence of the Hall effect in metals in the liquid state cannot be regarded as definitely proved.[1] In tellurium v. Ettingshausen and Nernst[2] found a decrease with rising temperature. Clough and Hall[3] failed to find any certain change in copper and phosphor-bronze between 20° and 300° C.

The behavior of the Hall effect in the magnetic metals is more interesting than its behavior in the non-magnetic, but the influence of temperature on the effect in the former has not been systematically studied. The temperature coefficient of the Hall effect in iron and cobalt is known only in the neighborhood of room temperature and the effect increases with rising temperature. Clough and Hall[3] studied nickel and steel for certain temperatures between 20° and 300° C. but for only two magnetic fields — 1,500 and 3,000 c.g.s. units. These investigators showed that in nickel the effect increases rapidly with rising temperature, reaches a maximum at about 290° C. and then decreases very rapidly. In steel the effect continues to increase with rise of temperature over the interval of temperature used in their experiments. Zahn and Schmidt[4] found that between — 186° and 23° C. the Heusler alloys behave with regard to temperature like the magnetic metals.

The attempts of Riecke,[5] Drude,[6] Lorentz,[7] Thomson[8] and others to account for the Hall effect and allied phenomena on the basis of the electron theory have emphasized the importance of a more detailed study of these effects, for any theory which can adequately account for them will be a large contribution to the electron theory of metals and will do much to explain the relations which exist between heat, electricity and magnetism. In view of the importance

[1] Zahn, ibid., p. 183.

[2] Acad. Wiss., Wien, Anz., pp. 173–174, 1886.

[3] Proc. Amer. Acad. of Arts and Sci. (28), pp. 189–199, 1892–3.

[4] Vehrh. d. D. Physik. Ges. (9), pp. 98–108, 1907.

[5] Ann. d. Phys. (66), p. 353, 1898.

[6] Ann. d. Phys. (1), p. 563, and (3), p. 369, 1900.

[7] Kon. Acad. Wet. Amst. (7), pp. 438, 585 and 684, 1905.

[8] Congres International de Physique (Paris), (3), p. 138, 1900. Corpuscular Theory of Matter, p. 99.

which such data might have in the electron theory, it seemed worth while to make a systematic study of a number of metals over as large a range of temperature as possible and over as large a range of magnetic fields as possible. It was especially interesting to examine the magnetic metals at temperatures above their respective critical temperatures in order to compare their behavior at such temperatures with the behavior of the non-magnetic metals. The desirability of data in this region has been recently pointed out by Zahn.[1] Furthermore, according to a suggestion made by J. J. Thomson[2] the reversal of the Hall effect in iron may be explained by supposing that the field actually acting on the free electrons is not only the impressed external field but also the field due to the orbital motion of the electrons in the metal. Under the action of the external field these electrons give fields which are in the opposite direction to the external field. The Hall effect would, therefore, consist of two terms of opposite signs. At temperatures above the critical temperature it seemed that the field due to the motion of the electrons in the molecules might be expected to nearly vanish. At such temperatures the Hall effect would consist of but one term and according to the electron theory would have the direction of the effect in bismuth. To test this theory was one of the purposes of this investigation.

Part I. of this paper concerns itself with the Hall effect in certain non-magnetic metals and silicon. Part II. deals with the magnetic metals.

Part I. Non-magnetic Metals and Silicon.

Method and Apparatus.

The method of observation was similar to that employed by other observers of this effect. The metals to be investigated were rolled to the desired thickness and then from the sheet were cut plates similar in form to those originally used by Professor Hall. These plates were in the form of rectangles 2.8 cm. long and 1.5 cm. wide. The thickness of the plates was determined from a knowledge of the density, area and weight of the plate. Strips of

[1] Ibid., p. 180.
[2] Ibid., p. 70.

copper 1.5 mm. in thickness were soldered along the ends of the plates. To these copper strips, which served as electrodes, were soldered the lead wires p and p' (Fig. 1) in such a way that the lines of flow were as nearly as possible parallel to the edges of the plate. From the middle of each side of the plate projected a narrow arm to which was soldered at the points s and s' respectively (Fig. 1) the copper lead wires which lead to the galvanometer on

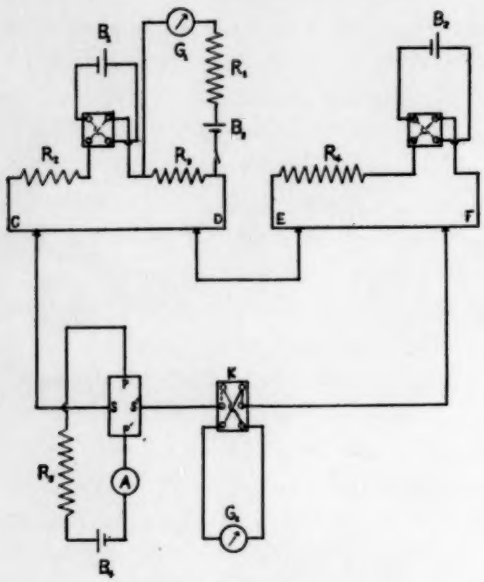

Fig. 1.

which the effect was to be observed. By filing these arms near the edge of the plate they could be shifted until they were nearly on the same equipotential line. In the cases of aluminum, gold and zinc the contacts for the lead wires at p and p' and those at s and s' could not be made by soldering. In these cases the ends of the plates were clamped between strips of copper and the lead wires for the current were soldered to these strips. The contacts for the wires to the galvanometer were made in a similar way by joining these wires by means of copper clamps to the arms at s and s'. After the lead wires had been connected to the plate in the way indicated above, the plate was mounted on a small rectangular piece

of hard fiber. It was held in position on the fiber by covering the plate and the fiber with paraffin. The plate thus mounted could be fastened in the plate-holder, which was made for this purpose and brought into the desired position in the magnetic field.

For the measurement of the electromotive force generated by the magnetic field the ordinary potentiometer method was used. The arrangement of the apparatus is shown diagramatically in Fig. 1, where pp' is the plate to be investigated. EF is an auxiliary potentiometer by means of which any lack of equipotentiality between s and s' and any thermo-electromotive forces in the circuit could be compensated. CD is the potentiometer for measuring the Hall electromotive force; B_1 is a storage battery of 2 volts; B_3, a standard cadmium cell of 1.0186 volts; G_1, a d'Arsonval galvanometer; R_3, a standard resistance of 900 ohms; R_2, the auxiliary resistance which could be adjusted in the usual way to make the drop of potential over R_3 equal to 1.0186 volts; B_4, a battery of 4 volts which sends the current through the plate pp'; R_5, an auxiliary resistance and G_2, a sensitive galvanometer of the Thomson type. On the potentiometer a copper slide wire with a resistance of .0004506 ohm per cm. was used.

When the plates had been placed in the proper position between the poles of the magnet, the position of the slider on the auxiliary potentiometer was adjusted until there was no deflection in the galvanometer G_2 on closing the key K. The magnet was then excited and the difference of potential between s and s' measured in the usual way on the potentiometer. In order to obtain one value of the Hall electromotive force plotted in the following curves, four readings were usually taken. With the current flowing from top to bottom of the plate and the magnetic field from left to right, one reading was made. Keeping the direction of the current fixed, the direction of the magnetic field was reversed and a second reading was made. The same process was repeated with the current flowing from bottom to top of the plate. The mean of these four observations was taken as the value of the Hall electromotive force. In some cases where the experimental difficulties were greater than usual, eight readings in all were taken and the mean of these has been plotted.

For the production of the magnetic fields a powerful electro-magnet was constructed. The pole-pieces were 10 cm. in diameter and tapered to 4 cm. at the air-gap. The exciting coils consisted of 2,850 turns of copper wire which could carry as much as 40 amperes. There was an arrangement for circulating water between the coils and the iron-cores. Some of the heat generated by the exciting current was thus carried away and the iron-cores kept at nearly constant temperature. At room temperature the length of the air-gap amounted to .9 cm. In the work at the temperature of liquid air the air-gap had to be increased to about 2.5 cm. to allow the introduction of the vessel containing the liquid air. The magnetic fields were measured ballistically with a flip-coil and a standard solenoid.

For the work at low temperatures it was necessary to provide for the liquid air a vessel which could be placed between the poles of the magnet. To use an ordinary Dewar flask for this purpose required that the pole-pieces of the magnet be very far apart and the magnetic fields correspondingly weak. A vessel somewhat similar to that used by van Everdingen[1] was finally adopted. A cross-section of this vessel together with a cross-section of the pole-pieces is shown in Fig. 2. It was a double-walled paper vessel with wooden top and bottom. Heavy drawing paper was used for the walls and the joints were rendered liquid-tight by means of glue. The horizontal section of that part of the vessel which was not between poles of the magnet was an ellipse, the major axis of which was 10.5 cm. and the minor axis, 7.0 cm. The part between the poles of the magnet was about 2.5 cm. thick, 10.5 cm. long and 7.0 cm. wide. The outer wall of the vessel had no bottom and when the top of the vessel had been completely closed by packing with cotton, the cold vapors from the air in the

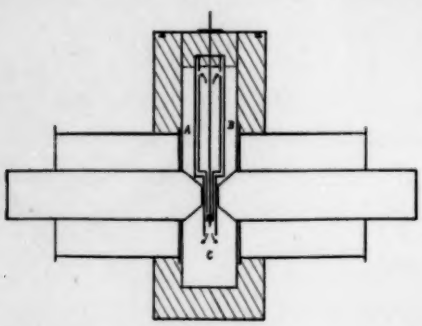

Fig. 2.

[1] Roy. Acad., Amsterdam, Proc. (3), 177–195, 1900.

vessel passed out through the openings at the top of the inner wall, down through the annular space between the walls and then out into the space *ABC* (Fig. 2), which was enclosed in a wooden box surrounded with cotton to make the insulation as good as possible. From the space *ABC* the cold vapor could come into the room. The circulation of cold vapor prevented to a large measure the evaporation of the air in the vessel, so that it was only necessary to refill with liquid air about once in forty-five minutes. A float served to indicate the height of the liquid air. At its top the vessel was fastened to a heavy brass plate which moved along suitable ways so that the vessel could be carried out of the magnetic field and the flip-coil which was mounted on the same brass plate could be carried into position for measuring the magnetic fields. The relative dimensions of the vessel and the magnet are indicated in Fig. 2, which has been drawn to scale. Before the mouth of the vessel was packed with cotton, the plate-holder which carried the plate to be studied was lowered into the liquid air and suitably clamped to the plate which carried the vessel. The proper distance to which the plate was to be lowered in order to bring it in the center of the magnetic field was determined before the vessel was placed between the poles of the magnet.

The temperature of the liquid air was not determined but was taken roughly as — 190° C. There seemed to be little point in knowing it with greater accuracy. The other temperatures were determined with a mercury-in-glass thermometer in the neighborhood of the plate.

Purity of the Metals.

The values of the Hall effect are known to be to a large degree a function of the purity of the metals, so that it is desirable to use in these experiments, metals which are as pure as possible. The platinum, silver and palladium were obtained from Kahlbaum. The copper, zinc and gold came from Eimer and Amend and were marked "chemically pure." The aluminum was of unknown origin and concerning its purity nothing can be said.

Results.

The results of these observations are plotted in Figs. 3 to 9 inclusive. In these figures the magnetic field in absolute units is

plotted for abscissæ and the Hall electromotive force in absolute units, for ordinates. It is seen from these figures that in the metals

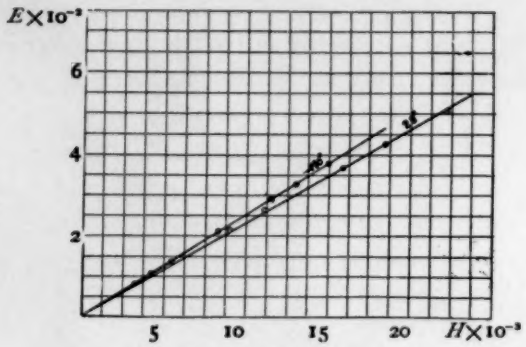

Fig. 3. Platinum.

studied in this paper the Hall electromotive force is proportional to the magnetic field at the temperature of liquid air as well as at room

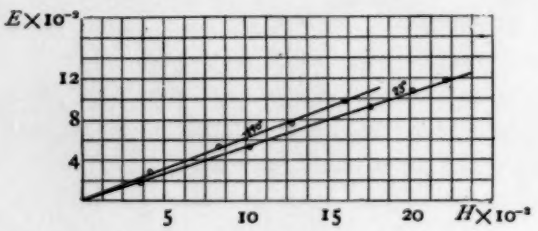

Fig. 4. Copper.

temperatures. Previous observers have shown that in the neighborhood of room temperature the relation between E, the Hall

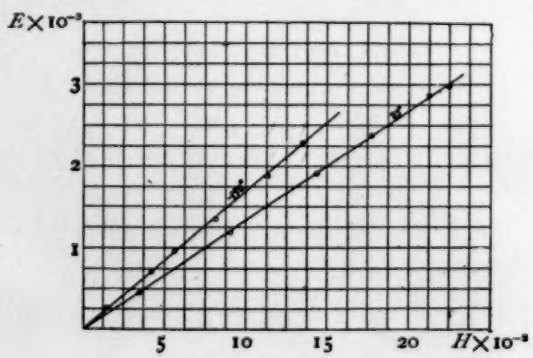

Fig. 5. Palladium.

electromotive force, i the current in the plate, H the magnetic field and d the thickness of the plate is expressed by the equation, $E = R \cdot Hi/d$, where R is a factor of proportionality which is independent of the electromotive force, the magnetic field, the current and the thickness of the plate. By means of this equation R has

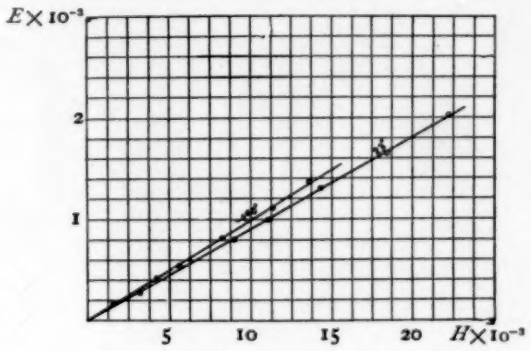

Fig. 6. Silver.

been calculated for the plates at room temperature and at the temperature of liquid air. In these calculations the current, the electromotive force and the magnetic field have been expressed in absolute units and the thickness of the plate in centimeters. The values of R thus obtained are given in Table I. The (+) sign in the fifth

TABLE I.

Metal.	Thickness, cm. × 10⁴.	Current, c.g.s.	Temp., ° C.	$R \times 10^4$	$\Delta R/\Delta t \times 10^7$
Platinum.	9.3	.104	−190	− 2.22	− 0.9
			23	− 2.02	
Copper.	27.1	.265	−190	− 6.5	− 5.1
			23	− 5.4	
Palladium.	6.65	.104	−190	−10.9	−11.0
		.103	23	− 8.6	
Silver.	9.5	.102	−190	− 9.2	− 4
			23	− 8.4	
Gold.	37.7	.265	−190	− 7.25	− 0.9
			25	− 7.04	
Zinc.	28.7	.265	−190	+10.9	−20
			25	+ 6.3	
Aluminum.	23.0	.265	−190	− 1.92	+ 6
			25	− 3.20	

column means that the effect has the direction of the effect in iron and the (−) that it has the direction of the effect in bismuth. In

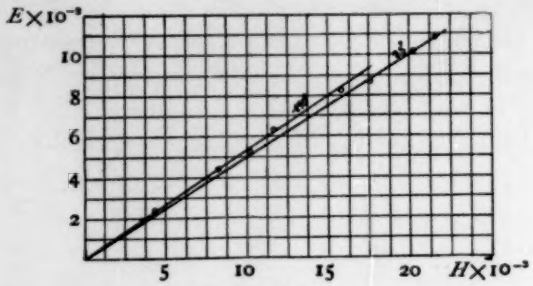

Fig. 7. Gold.

the last column of this table is given the average change in R per degree between the temperature of liquid air and room temperature. The (+) in this column means that the magnitude of R increases

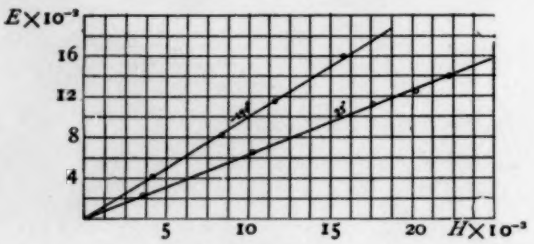

Fig. 8. Zinc.

with rising temperature and the (−) that it decreases with rising temperature. In silver, gold, platinum, palladium, zinc and copper the effect increases as the temperature is decreased from room tem-

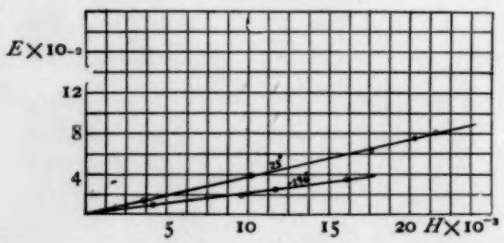

Fig. 9. Aluminum.

perature to that of liquid air. This increase is greatest in zinc where it amounts to about 70 per cent. of the value at room temperature;

and least in gold, where it is only about 3 per cent. of the value at room temperature. In the specimen of aluminum studied in this paper a lowering of the temperature causes a decrease in the Hall effect. This is the only one of the non-magnetic metals in which such a decrease was found. How much influence the impurities of the aluminum had on this result it is impossible to say.

For purposes of comparison some of the values of R obtained by previous observers are given in Table II. It will be seen that in

TABLE II.

Metal.	$R \times 10^4$	Observer.
Gold	−6.6	Hall
	−7.1	Ettingshausen and Nernst
	−7.04	Smith
Copper	−5.4	Zahn
	−5.2	Ettingshausen and Nernst
	−5.4	Smith
Platinum	−1.27	Zahn
	−2.4	Ettingshausen and Nernst
	−2.02	Smith
Silver	−8.97	Zahn
	−8.3	Ettingshausen and Nernst
	−8.4	Smith

the purer and better defined metals they agree well with the values obtained in this work.

Silicon.

The Hall effect has been studied by Miss Wick [1] in two specimens of silicon. One of these specimens contained 95 per cent. of silicon; the other contained 99 per cent. The direction of the effect in each of these specimens was the same as the direction of the effect in bismuth. The magnitude of the effect was greater in the specimen which contained 99 per cent. of silicon than in the specimen which contained 95 per cent. She also found that the prediction of Beattie [2] concerning the relation between the thermo-electromotive forces and the rotary coefficients of the Hall effect was verified for silicon. Beattie pointed out that metals and alloys which occupy extreme positions in the thermo-electric series will occupy similar

[1] PHYS. REV. (27), p. 76, 1908.

[2] Roy. Soc. Edinb. Proc. (20), p. 481, and (21) p. 146.

positions in a series of rotary coefficients. Miss Wick found that silicon occupied in the thermo-electric series a position above that of bismuth and that in a series of rotary coefficients, the rotary coefficient of silicon also stood above that of bismuth. Mr. C. I. Zimmermann who was working in the physical laboratory of this university on the electric properties of silicon found that in most of the specimens which he studied, the current flowed from copper to silicon across the hot junction of a copper-silicon couple. As these specimens which were known to be very pure, gave thermo-electromotive forces in the direction opposite to that given by Miss Wick, it seemed of interest to examine the Hall effect in some of them in order to see whether a reversal of the thermo-electromotive force is accompanied by a reversal of the Hall effect. Since Miss Wick did not determine the relation between the Hall electromotive force and the magnetic field, it seemed worth while to determine this relation.

By means of a wire-saw fed with carborundum powder the plates were cut from irregular pieces of silicon which had crystallized from a reservoir of molten silicon. With a rotating disc on which carborundum powder was used for an abrasive, the plates were ground down to the desired thickness. The contacts for the wires which lead from the plate to the battery were made by copper-plating the ends of the plate for a width of .4 cm. and then soldering the copper lead wires to these regions. The contacts for the wires which lead to the galvanometer were made in a similar way by copper-plating a small region in the middle of the edge of the plate and then soldering fine lead wires to these copper-plated regions, which had been filed down to make them as small as possible.

Five plates were used in these experiments. They were cut from three different specimens of silicon. These specimens will be referred to as specimens *A*, *B* and *C*. Analyses of these specimens were kindly made by Mr. F. J. Tone, of the Carborundum Company, of Niagara Falls, for which kindness the author is very grateful. The analyses of the specimens gave the following results.

	SiC	Fe	Al	Si
Specimen *A*	Trace	.41%	.17%	99.4%
Specimen *B*	Trace	.32	.14	99.5
Specimen *C*	.85	1.89	.73	96.5

Plates I., II. and III. were made from specimen *A*; Plate IV. from *B*; and Plate V. from *C*. Plates I. and II. were from a slice of silicon which was cut from that part of specimen *A* which had been first to crystallize. A second slice parallel to the first was also cut from specimen *A* and from it was made Plate III. Plates I., II., III. and IV. were very homogeneous and free from perforations of any sort. Plate V. contained two small pin-holes but since they were covered by the copper-plating, they could have little influence on the distribution of the current in the plate. This plate was too small to allow a satisfactory determination of the Hall effect and was used only to get the order of magnitude and the direction of the effect.

Table III. contains the values of *R* for Plates I., II., III. and IV. In Fig. 10 have been plotted the curves showing the relation between

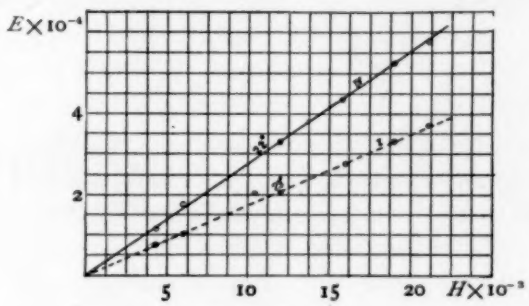

Fig. 10. Silicon.

the Hall electromotive force and the magnetic field. The dotted curve is for Plate I. and the continuous curve for Plate IV. Similar curves were obtained for Plates II. and III. but since they differed in no way from the curves for Plates I. and IV. they have not been included in this paper. The direction of the Hall effect in

TABLE III.

Silicon.

Plate.	Thickness, cm.	Current, c.g.s.	Temperature, C.	*R*
I.	.244	.0102	23°	41.0
II.	.179	.0103	22°	48.7
III.	.189	.0102	22°	59.8
IV.	.153	.0102	22°	40.0

each of these plates was opposite to the direction of the effect in bismuth. Each of these plates was found to have a thermo-electromotive force which made the current flow from copper to silicon across the hot junction of the copper-silicon couple. In Plate V. the Hall electromotive force was found to have the same direction as that electromotive force in bismuth. The rotary coefficient could not be accurately determined in this plate but its order of magnitude was about 20, where all of the quantities involved in it are measured in the same units in which they were measured in the other plates. The thermo-electromotive force in this plate had the opposite direction to that in Plates I., II., III. and IV. The results for Plate V. agree completely with the results obtained by Miss Wick both with regard to the direction of the Hall effect and with regard to the direction of the thermo-electromotive force. On the other hand in the other plates both the Hall electromotive forces and the thermo-electromotive forces are in directions opposite to their respective directions in Plate V. It seems, therefore, that in some specimens of silicon the Hall effect has the direction of the effect in bismuth and in other specimens it has the direction of the effect in iron. In some specimens the current flows from copper to silicon across the hot junction of a copper-silicon couple and in other specimens the current flows in the opposite direction. It is worthy of note that the direction of the Hall effect in the purer specimens is the direction of the effect in iron. From the study made in this paper it is impossible to say that the reversal of the effect is due to the presence of impurity in the silicon. Whatever be the cause of the reversal it appears that a reversal of the thermo-electromotive force is accompanied by a reversal of the Hall effect.

From Fig. 10 where the curves showing the relation between the Hall electromotive forces and the magnetic fields are plotted it will be seen that within the range of these observations the Hall electromotive force is proportional to the magnetic field.

PART II. MAGNETIC METALS.

Method and Apparatus.

The method of observation in the work at room temperature and at the temperature of liquid air was precisely the same as the method

employed in Part I. of this paper on non-magnetic metals. For temperatures above room temperature some additional apparatus had to be constructed to secure the desired temperatures and to overcome experimental difficulties.

In order to obtain the three temperatures 100°, 184° and 300° C. a vapor-bath of the form indicated in Fig. 11*a* and 11*b* was constructed. Fig. 11*a* shows a section perpendicular to the axis of the pole-pieces and Fig. 11*b* a section by a plane determined by the axis of the pole-pieces and the vertical. The vessel was made of brass and the joints were brazed. It was provided with the ordinary form of metal condenser. The space *A* was 18 cm. long, 7 cm. wide, and 2 cm. thick at the top and 1 cm. thick at the bottom where it was between the pole-pieces. Into this space the plate-holder could be lowered and fastened precisely as in the liquid air vessel. The mouth of the space *A* was packed with asbestos to prevent the circulation of the air. The liquids used in the bath were water, aniline and diphenylamine boiling under atmospheric pressure.

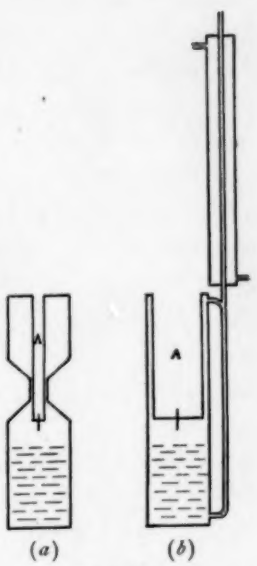

Fig. 11.

For the realization of temperatures between 300° and 900° C. an electric furnace was constructed. The heating coil was made of nichrome wire wound on a copper box, 18 cm. long, 9 cm. wide and 1 cm. thick. Before winding with wire the box was covered with mica for purposes of insulation. After the heating coil had been wound on the box it was covered with a paste made of water-glass and magnesium oxide. The copper box and the heating coil were placed inside of a brass-jacket which was 25 cm. long, 12 cm. wide and 2.5 cm. thick. The space between the heating coil and the jacket was filled with infusorial earth to prevent as far as possible the loss of heat. The parts of the walls of the jacket which were opposite the pole-pieces were made of mica to reduce the flow of heat into the pole-pieces with the resulting cooling of that part of the furnace between the pole-pieces.

Since neither the copper box nor the nichrome wire would stand temperatures above 900° C. the electric furnace had to be somewhat modified for the temperatures between 900° and 1100° C. A box 20 cm. long, 9 cm. wide and 1 cm. thick was built up out of plates made by baking magnesium oxide mixed with a small amount of aluminum oxide in a graphite mould which was heated in an electric furnace to about 1600° C. The thickness of these plates was about 2 mm. On the outside of this box platinum foil, which served as the heating coil, was wound. The box with the heating coil was then placed in a brass box, 25 cm. long, 12 cm. wide and 3.5 cm. thick. The space between the brass box and the heating coil was filled with infusorial earth which gave satisfactory insulation.

For temperatures between 100° and 400° C. the connections for the lead wires from the battery to the plate and those from the galvanometer to the plate were made by means of copper clamps to which were hard-soldered the lead wires. These clamps were mounted at the desired distances on a sheet of brass from which they were insulated by a sheet of mica. After the plate had been put in position and clamped between the electrodes, the plate and electrodes were covered with sheets of mica and all held in position by a thin sheet of brass fastened by means of screws to the brass plate carrying the electrodes. This clamping of the plates between sheets of mica prevented them from being pulled out of position by the magnetic field.

At temperatures above 400° C. provision had to be made against the oxidation of the plate. During the work at temperatures less than 900° the plates and electrodes were mounted inside of a thin copper box which was nearly air-tight. A photograph of that part of the box which contained the plate and the electrodes is shown in Fig. 12. The plate and the electrodes were insulated from the box by sheets of mica, and the lead wires by small magnesia tubing. Copper lead wires were used with this box. For temperatures above 900° C. a nickel box and nickel electrodes were substituted for the copper box and electrodes and the copper lead wires were replaced by platinum wires. In other respects the arrangement was precisely the same as with the copper box. Sheets of mica were placed underneath and on top of the plate in such a way

that after the two halves of the box had been fastened together with screws, the magnetic field could not produce a displacement of the plate. The interior of this box was connected by means of a tube of small bore to a hydrogen generator. The hydrogen which had been generated in the usual way was allowed to flow through

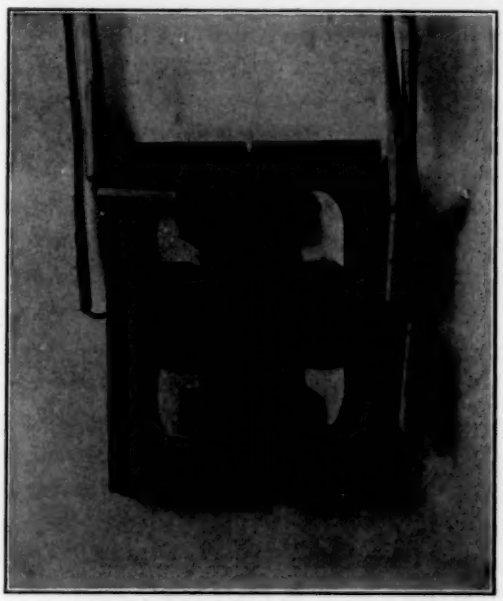

Fig. 12.

the space containing the plate and the electrodes for some time before heating and for the entire time the plates were above 300° C. To remove the oxygen and any water vapor from the hydrogen it was made to flow through sulphuric acid, over heated copper oxide and through phosphorous pentoxide before entering the box. By this method it was possible to prevent almost entirely the oxidation of the plates.

Measurement of Temperatures.

The temperatures up to and including 300° C. were determined with the mercury-in-glass thermometer referred to in Part I. of this paper and those above 300° were determined by means of a platinum-platinum-iridium thermal couple which had been calibrated

over the interval of temperature used in these experiments. The temperatures used for this calibration were the boiling point of water, the boiling point of sulphur and the melting point of gold.

Purity of the Metals.

The cobalt, nickel and iron were obtained from Kahlbaum. The electrolytic iron was kindly furnished by Professor Watts, of the electrochemical department of the University of Wisconsin. It was prepared according to the method of Burgess and Hambuechen[1] and was known to be very pure. After having been deposited it had been annealed by heating in a hydrogen bath to about 1200° C. For purposes of comparison a plate of nickel furnished by H. J. Slaker, of the United States Mint, was also examined.

In the work at the temperature of liquid air it was necessary to use thinner plates than had been used at ordinary temperatures, because the effect becomes so small in liquid air that it can no longer be observed with accuracy in any except very thin plates. Certain accidents to the plates in the course of the experiments made it necessary to work on more than one plate of the same metal. At some of the high temperatures it was also desirable to make the observations on thinner plates than had been used at lower temperatures in order to overcome some of the error due to thermo-electromotive forces in the circuit. All of the plates for any particular metal were cut from the same sheet of metal which had been treated in precisely the same way and was originally not more than 8 or 10 cm. square. The purity of the plates for any particular metal must have been nearly the same. All of the work on the electrolytic iron was done on the same plate but in some preliminary experiments before satisfactory means for preventing oxidation had been devised, it became somewhat oxidized and in removing this layer of oxide the thickness was reduced from .0148 cm. to .0133 cm.

Results.

The results for the magnetic metals have been plotted in Figs. 13–19 inclusive. Each value plotted in these curves is the mean of at least four observations taken in the way indicated in Part I.

[1] Iron and Steel Mag. (8), p. 48, 1904.

In these figures the Hall electromotive forces in absolute units have been plotted for ordinates and the magnetic fields for abscissæ. The current in the plate for which all of these curves have been plotted was 1.04 amperes. Where the current in the plate when the observations were made differed slightly from this value, suitable correction was made on the basis that the Hall electromotive force is proportional to the current.

In plotting these curves showing the relation between the Hall electromotive force and the magnetic field, it was necessary to take account of the fact that, for reasons given above, all of the observations for a particular metal were not made on the same plate but on plates of different thicknesses. Previous observers have shown that the Hall electromotive force for a particular magnetic field and for a given current is inversely proportional to the thickness of the plate. If the Hall electromotive force has been observed in a plate of known thickness for a given magnetic field and current, it is possible by means of this relation to calculate the electromotive force which would have been observed in any other plate of the same metal for the same magnetic field and current. In this way the electromotive forces where necessary have been calculated so that the values plotted in Fig. 13 are for a plate of nickel .0185 cm. thick; in Fig. 14 and Fig. 15 for a plate of Kahlbaum iron .0089 cm. thick; in Fig. 16 and Fig. 17 for a plate of electrolytic iron .0148 cm. thick; and in Fig. 18 and Fig. 19 for a plate of cobalt .0213 cm. thick.

Nickel.

From Fig. 13 where the curves showing the relation between the Hall electromotive force and the magnetic fields are plotted for Kahlbaum nickel for various temperatures, it will be seen that for temperatures not greater than 385° C. the electromotive force is at first proportional to the magnetic field and that when the field is increased beyond a certain value which is a function of the temperature, a sort of saturation occurs after which a further increase in the field produces a small but perfectly definite increase in the Hall electromotive force. As the temperature is raised from — 190° to 385° C., the magnitude of the field necessary to produce saturation becomes less and less. At the former temperature it requires about

8,000 c.g.s. units for saturation; at the latter about 1,000 c.g.s. units. For all temperatures not greater than 355° C. the slopes of the curves beyond saturation is nearly the same, although their slopes before saturation are quite different. The magnitude of the effect at the temperature of liquid air before saturation is about one twenty-third of its magnitude under the same conditions at 300° C. and the magnitude at 410° is about one ninth of that at 300° C. For fields of equal intensity the Hall electromotive force at 355° is

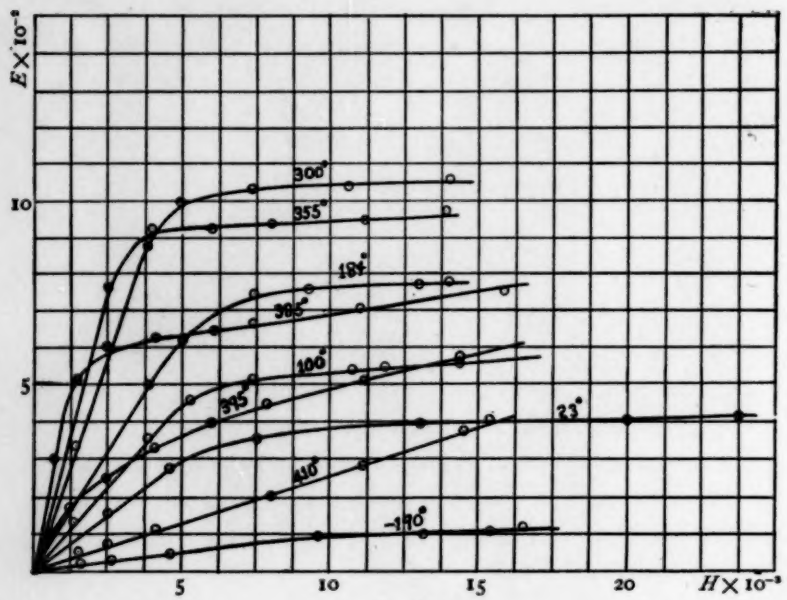

Fig. 13. Nickel.

greater than that at 300° until the field has the value of approximately 3,750 c.g.s. units but for fields greater than 3,750 units the effect is greater at 300° than at 355° C. For fields above 2,000 c.g.s. units the effect is much smaller at 385° than at 300° C. At the former temperature when the magnetic field exceeds 2,000 c.g.s. units, that part of the curve showing the relation between the Hall electromotive force and the magnetic field is no longer nearly horizontal but has been rotated through a certain angle. This rotation is seen more clearly in the curve for 395° C. When the temperature has been raised to 410° all sign of change of slope in the curves

has disappeared and the effect is proportional to the magnetic field for all fields used in these experiments. When the critical temperature has been passed, a further increase of temperature causes a decrease in the magnitude of the effect. At these temperatures nickel behaves like non-magnetic metals.

The results for the nickel from the United States Mint agreed except for small differences in magnitude with the results for the Kahlbaum nickel. Since these results brought out no new points, it has not seemed worth while to include them in this paper.

Kahlbaum Iron.

In Figs. 14 and 15 are plotted for the Kahlbaum iron the curves analogous to those plotted in Fig. 13 for nickel. Because the effect

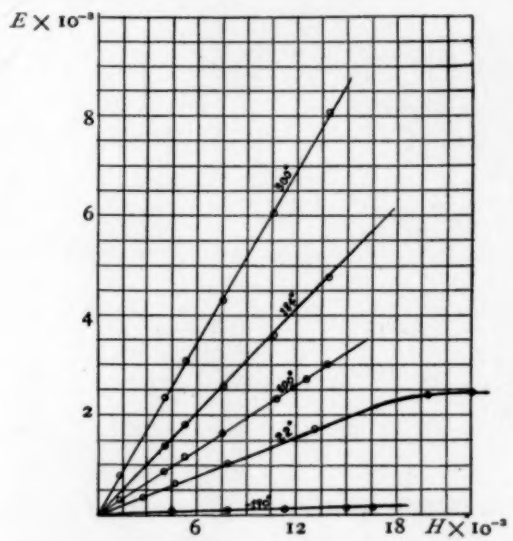

Fig. 14. Kahlbaum iron.

in iron varies between such wide limits for the temperatures used in these experiments it was necessary to plot the curves on two different scales. Fig. 14 contains the curves for temperatures between −190° and 300° inclusive and Fig. 15 the curves between 300° and 900° on a different scale. The value of the effect at −190° is only about one four-hundredth of the value at 735° and the value at 900° is approximately one thirty-fifth of the value at 735° C. The fields

required for saturation are so large that at temperatures less than 545° C. it was only possible to reach saturation at room temperature, where the distance between the pole-pieces being small, the intensity of the magnetic field could be made as much as 22,000 c.g.s. units. When the temperature had been raised to 545° C., the point at which saturation occurred had shifted toward lower fields, so that

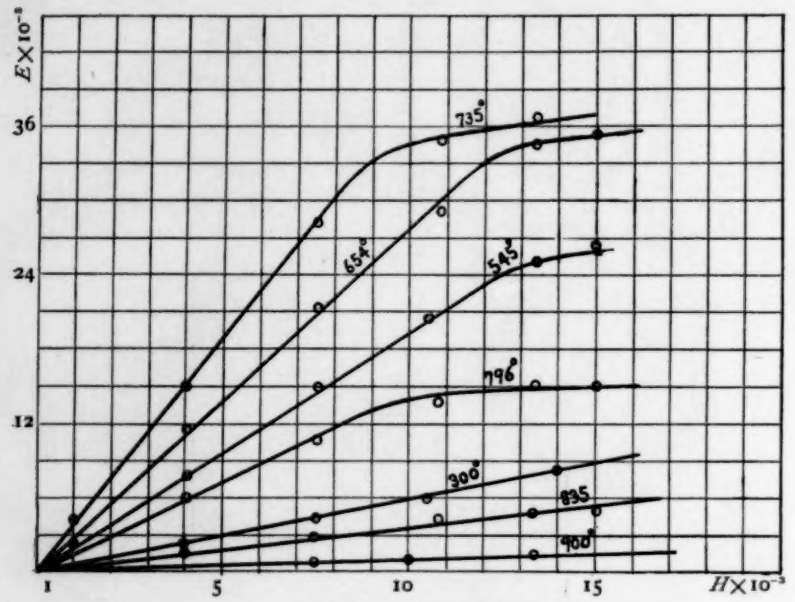

Fig. 15. Kahlbaum iron.

it appeared in the neighborhood of fields with an intensity of about 13,000 c.g.s. units. Further increase of temperature caused saturation to shift still more toward lower fields and at 735° C. it occurred when the field was about 10,000 c.g.s. units. The shift between 735° and 796° C. is small and nearly within the error of observation. In another plate of Kahlbaum iron this shift for the corresponding range of temperature was somewhat more certain, so that there can be no doubt of a shift toward lower fields for this interval of temperature. It is impossible to say that the shift between 22° and 545° C. is continuous, because the fields necessary for saturation at intermediate temperatures could not be realized under the conditions of this experiment. From later considerations it will appear probable that there

is a continuous shift between 22° and 796° C. For temperatures somewhat above 800° the Hall electromotive force is proportional to the magnetic field, for the range of fields used in these experiments. Just as in the case of nickel the temperature coefficient of the effect reverses sign when the critical temperature is crossed. The direction of the effect on the two sides of the critical temperature is the same and opposite to the direction of the effect in bismuth. At 1000° C., the highest temperature at which the iron was studied, the effect had become so small and the thermo-electromotive forces so large that it was impossible to determine the magnitude of the effect with any certainty but its direction was the direction of the effect at the other temperatures. There is no reversal of the direction of the effect of iron between — 190° and 1000° C.

Electrolytic Iron.

The curves in Fig. 16 and Fig. 17 for electrolytic iron have the same form as the corresponding curves for Kahlbaum iron. No

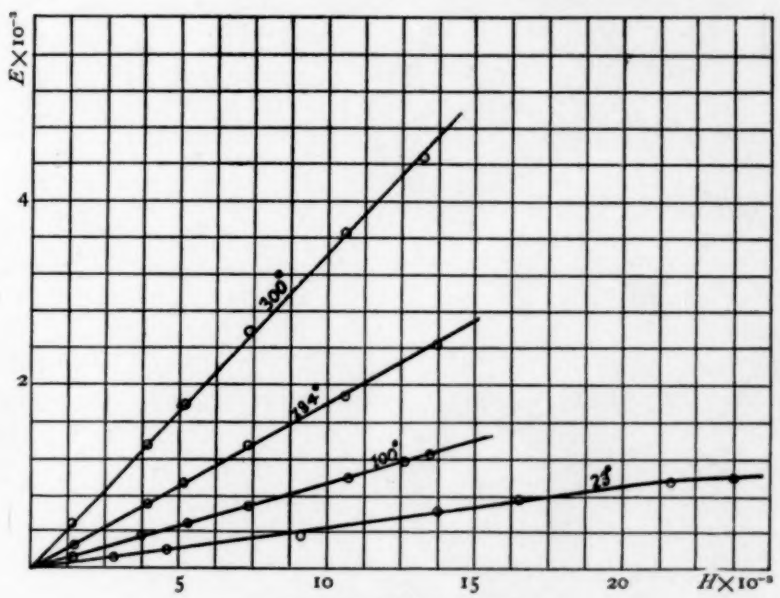

Fig. 16. Electrolytic iron.

observations were made on this plate at the temperature of liquid air. The shifting of the bends in these curves is in every way

similar to the shifting of the bends in the curves for the Kahlbaum iron. In addition to confirming the results on the Kahlbaum iron, these data show that the magnitude of the effect at room temperature is much smaller in electrolytic iron than in Kahlbaum iron.

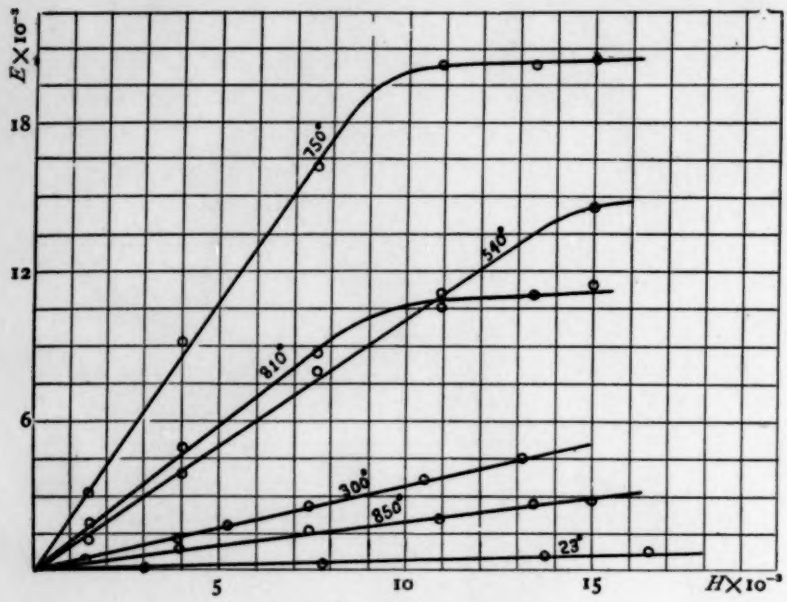

Fig. 17. Electrolytic iron.

On the other hand, the rate at which the effect increases with rising temperature between 23° and 780° C. is greater in the electrolytic iron than in the Kahlbaum iron, so that at the critical temperature the effect in the former is nearly equal to the effect in the latter. Since the electrolytic iron was much purer than the Kahlbaum iron, these results suggest that the purest iron has the least Hall effect at ordinary temperatures and the greatest temperature coefficient of the effect.

Cobalt.

The curves for cobalt in Figs. 18 and 19 do not differ essentially in form from those for iron and nickel in the preceding figures. For fields less than those necessary to produce saturation the magnitude of the effect at — 190° is not more than three fourths of one

per cent. of its magnitude at 960° and the magnitude at 1,100° is about one fourth of the magnitude at 960° C. For temperatures above the critical temperature of cobalt it was not possible to get satisfactory curves showing the relation between the Hall electromotive forces and the magnetic fields. The thermo-electromotive forces become so troublesome at these temperatures and the variation of the effect with the temperature is so rapid that accurate observations were quite impossible. Moreover, the highest fields to be obtained for temperatures above 900° C. only amounted to 9,300

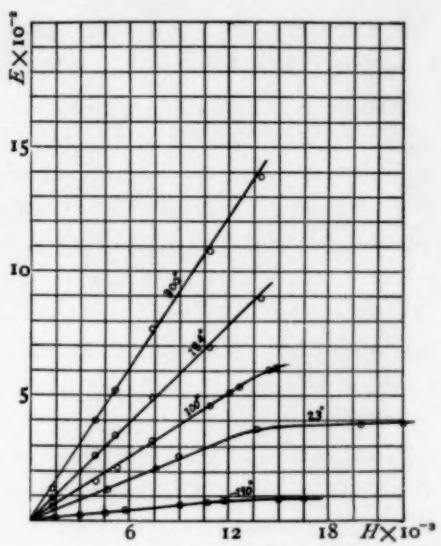

Fig. 18. Cobalt.

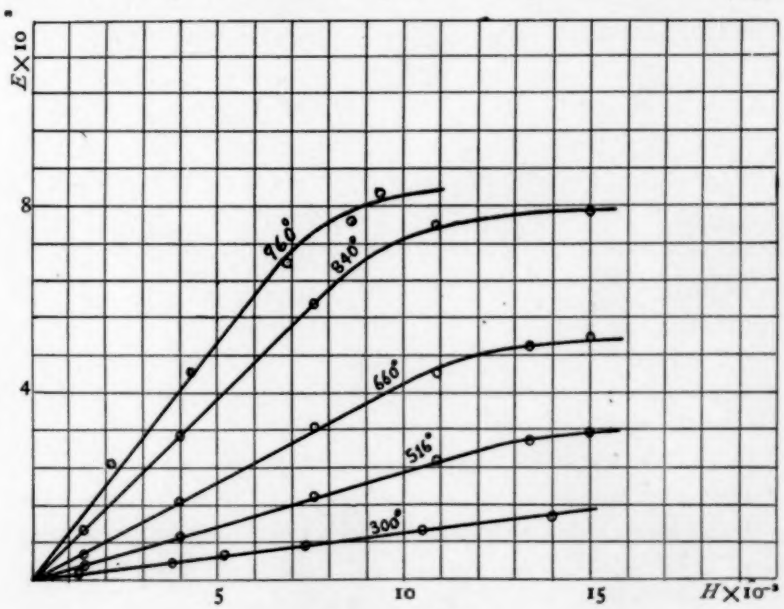

Fig. 19. Cobalt.

c.g.s. units, because the pole-pieces had to be 3.5 cm. apart in order to allow the introduction of the electric furnace at these temperatures. The range of magnetic fields was, therefore, much less than it had been in the other experiments. It was, however, possible to obtain two approximate values, one at 1030° and the other at 1100° C. The magnetic field had an intensity of 8,600 c.g.s. units. These values have been plotted in Fig. 23. Although they are approximate, large errors in them would not in any important way affect the character of the curve in that figure. At either of these temperatures the Hall electromotive force seemed to be proportional to the magnetic field but the range of fields was so small and the observations so inexact that not much importance could be attached to these results. It is to be noted that saturation in cobalt occurs at fields which are more intense than those necessary for saturation in nickel and less intense than those for saturation in iron. It will appear later that there is a relation between the maximum value of the intensity of magnetization and the fields necessary for saturation, and from this relation the fact noted above will find explanation. As the temperature of the cobalt is raised from — 190° to 300° C., the saturation points shift toward higher fields. A further increase of temperature causes the saturation points to shift back to lower fields. The behavior of cobalt in this respect is to be contrasted with that of iron and nickel in which an increase of temperature seems to cause a continuous shift of the saturation points toward lower fields. The explanation of this difference in behavior will be presented in a later paragraph. The curves for cobalt like those for iron and nickel become nearly horizontal after saturation has been reached.

According to Kundt[1] the Hall electromotive force in the magnetic metals is proportional to the intensity of magnetization and not to the magnetic field. Saturation would occur in the curves plotted in this paper, when the intensity of magnetization had reached its maximum value. The work of Honda and Schimizu[2] has shown that in the case of iron and nickel, the maximum value of the intensity of magnetization is greatest at the temperature of liquid air and with

[1] Wied. Ann. (49), pp. 257–271, 1893.
[2] Phil. Mag. (6), [10], pp. 548 and 642, 1905.

rising temperature decreases to almost zero at a temperature somewhat above the critical temperature. The rate of decrease is a function of the temperature and is largest for temperatures which are in the neighborhood of the critical temperature. In the case of cobalt, however, the variation of the maximum value of the intensity of magnetization with the temperature is quite different from what it is in iron and nickel. From its value at — 186° C. the maximum value of the intensity of magnetization in cobalt increases with rise of temperatue to a maximum at 300° C., then decreases with further rise of temperature in a way similar to that in which it is found to behave in nickel and iron.

If the Hall electromotive force is proportional to the intensity of magnetization, the bends in the curves should occur when the metals are saturated. If 4π is taken as the demagnetizing factor for a thin plate, H', the magnetic field inside of the plate for a particular temperature is given by the equation $H' = H - 4\pi I$, where H is the field in the air-gap before the plate was introduced and I the intensity of magnetization in the plate. If by increasing H, H' is increased in such a value that I becomes a maximum, any further increase in H will not increase the Hall electromotive force. Let I_m denote the value of the intensity of magnetization when the metal is saturated. Since H' is small in comparison with H and $4\pi I_m$, at saturation $4\pi I_m = H$ approximately. The values of I_m were not known for the plates used in these experiments but taking the values from the data of Honda and Schimizu it is found that the bends in the curves occur roughly, when $H = 4\pi I_m$. The fact that I_m is greatest for iron and least for nickel, offers the explanation for the fact that the fields necessary for saturation are greatest in iron and least in nickel. The fact that with increasing fields the Hall electromotive force continues to increase after the plate is in condition here referred to as saturation, may be due to the fact that the metal never becomes completely saturated or it may be that the Hall electromotive force is not exactly proportional to the intensity of magnetization.

Since according to the data of Honda and Schimizu the maximum value of the intensity of magnetization decreases from liquid air to the critical temperature in the case of iron and nickel, the bends in these curves with rising temperature should shift continuously

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Since according to the data of Honda and Schimizu the maximum value of the intensity of magnetization decreases from liquid air to the critical temperature in the case of iron and nickel, the bends in these curves with rising temperature should shift continuously

toward lower fields, for $4\pi I_m$ is less for high than for low temperatures. It has been seen that this is precisely what happens in the case of nickel. In the case of iron it was seen that there is also a shift toward lower fields with rising temperature. For the reasons given above it was not possible to determine whether the bends shift continuously between 22° and 545° toward lower fields. Such a shift is, however, very probable. It has already been pointed out that the bends in the curves for cobalt instead of shifting continuously toward lower fields with rising temperature, shift toward higher fields as the temperature rises from — 190° to 300° and then shift toward lower fields with further rise of temperature. It will be recalled that the maximum value of the intensity of magnetization was found to increase up to 300° C. and then to decrease. It seems that an increase in the maximum value of the intensity of magnetization causes an increase in the field necessary to produce saturation and that a decrease in the former causes a decrease in the latter. The temperature at which the bend in cobalt occurs at the highest field is about 300° C. which is nearly the temperature at which the maximum value of the intensity of magnetization has its largest value.

Rotary Coefficients.

It has been shown that in the non-magnetic metals the relation between E, the Hall electromotive force; i, the current in the plate; H, the magnetic field; and d, the thickness of the plate, is expressed by the equation $E = R \cdot Hi/d$ where R is a factor of proportionality independent of the current, the thickness of the plate, the magnetic field and the electromotive force. This equation holds for the magnetic metals, until the field has reached the value at which saturation begins to appear. For fields greater than these the equation no longer holds, although the curves after saturation seem to be straight lines with slopes very different from the slopes before saturation.

The values of R calculated from this equation are given in Table IV. for Kahlbaum nickel; in Table V. for Kahlbaum iron; in Table VI. for electrolytic iron; and in Table VII. for cobalt. The units in which current, electromotive force, magnetic field and thickness of the plate have been expressed are those used for the corre-

TABLE IV.

Nickel.

Thickness, cm. $\times 10^3$.	Current, c.g.s.	Temperature, C.	$R \times 10^3$	$\Delta R/\Delta t \times 10^5$
2.87	.108	−190°	1.85	
18.5	.103	23°	12.7	+ 5
18.5	.104	100°	16.3	5
2.87	.103	184°	23.4	8
2.59	.104	300°	40.8	15
2.59	.104	355°	56.0	28
2.59	.103	385°	58.9	—
2.59	.104	395°	19.2	−400
2.59	.104	410°	4.5	−100
2.59	.104	546°	0.7	− 3

sponding quantities in Part I. of this paper. The last column of each of these tables contains the average change in R per degree over the successive intervals of temperature, which are given in the third column of the corresponding table. The first column gives the thickness of the plate and the second column the current in the plate.

TABLE V.

Kahlbaum Iron.

Thickness, cm. $\times 10^3$.	Current, c.g.s.	Temperature, C.	$R \times 10^3$	$\Delta R/\Delta t \times 10^4$
3.32	.103	−190°	0.75	
8.9	.105	22°	11.0	+ 0.5
8.9	.104	100°	18.9	1.0
3.32	.104	184°	29.2	1.2
3.32	.105	300°	50.4	1.8
9.04	.105	545°	167	4.4
9.04	.105	654°	243	7.0
9.04	.105	735°	319	9.3
9.04	.105	796°	120	−60
9.04	.105	835°	32.8	−23
9.04	.105	900°	9.0	− 3.7

The relation between R, this factor of proportionality, and T, the absolute temperature of the plate, is brought out in Fig. 20 for Kahlbaum nickel; in Fig. 21 for Kahlbaum iron; in Fig. 22 for electrolytic iron; and in Fig. 23 for cobalt. In these figures the absolute temperatures of the plate are plotted for abscissæ and the

TABLE VI.

Electrolytic Iron.

Thickness, cm. $\times 10^3$.	Current, c.g.s.	Temperature, C.	$R \times 10^3$	$\Delta R/\Delta t \times 10^4$
1.48	.105	23°	6.6	
1.48	.103	100	13.5	+ 0.9
1.48	.104	184	24.7	1.3
1.48	.104	300	49.3	2.1
1.33	.104	540	139	3.7
1.33	.104	664	229	7.3
1.33	.104	750	302	8.5
1.33	.104	810	162	−47.0
1.33	.104	850	30	−33.0

TABLE VII.

Cobalt.

Thickness, cm. $\times 10^3$.	Current, c.g.s.	Temperature, C.	$R \times 10^3$	$\Delta R/\Delta t \times 10^5$
6.34	.103	− 190°	1.51	
21.3	.103	23	5.88	+ 2.0
21.3	.104	100	8.65	3.6
6.34	.104	184	13.6	5.9
6.34	.104	300	21.2	6.6
6.34	.105	516	48.3	12.5
6.34	.104	660	89.4	28.5
6.34	.104	840	158	38.0
21.3	.105	960	200	35
21.3	.105	1,030	170	−200
21.3	.105	1,100	60	−130

values of R for ordinates. It will be seen from these curves that R increases with rise of temperature until the critical temperature of the metal is reached and that the rate of increase of R also increases up to the critical temperature. In going above the critical temperature a few degrees the value of R drops suddenly to a small fraction of its value at the critical temperature. In the case of iron and nickel R continues to decrease more and more slowly with further rise of temperature and the curve seems to approach asymptotically the axis of temperature. In case of cobalt it was not possible to follow the curve far enough to determine whether it also approaches asymptotically the axis of temperature. The

reason for not studying the cobalt above 1100° C. was the fact that at temperatures above 1100° C. the mica used for insulation almost fused and became a sufficiently good conductor to make further observations impossible.

The curve given in Fig. 20 is similar to that given by Clough and Hall,[1] although the temperature at which the decrease in R begins is higher in the curve given in this paper than in their curve. This discrepancy may be attributed to difference in purity of the nickel in the two cases.

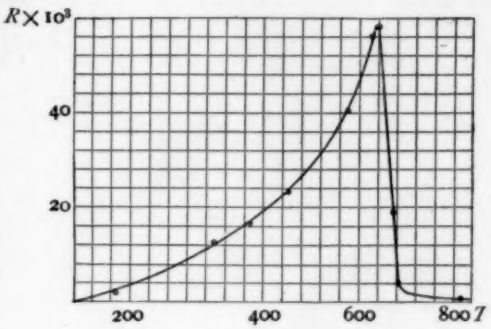

Fig. 20. Nickel.

Reversal of the Hall Effect in Iron.

In the discussion of the reasons for the reversal of the Hall effect in iron and its failure to be always proportional to the magnetic field J. J. Thomson[2] has pointed out that in addition to the effect of the magnetic force on the electrons, while they are moving over their free paths, one must take into account the magnetic force which acts on the electrons when collisions between electrons and molecules occur. Thomson states this possible explanation of the reversed effect in iron as follows: "Imagine a body whose molecules are little magnets. Then if the body is placed in a magnetic field so that the lines of force are vertical and downwards, the molecules will arrange them-

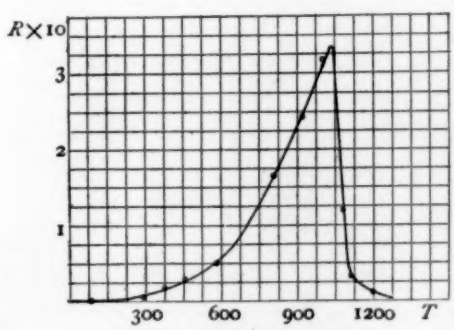

Fig. 21. Kahlbaum iron.

[1] Ibid., pp. 189–199.

[2] Corpuscular Theory of Matter, p. 70.

selves so that their axes tend to be vertical, the negative poles being at the top, the positive poles at the bottom. Then close to the magnet, in the region between its poles, the lines of force due to the magnet will be in the opposite direction to those due to the magnetic field and the intensity of the magnetic force close to the magnet may be very much greater than that of the external field. In this case when a corpuscle came into collision with a molecule the velocity would be rotated in the opposite direction to its rotation by the magnetic field before collision with the magnet — while it was moving over its free path. In this case the Hall effect would consist of two terms, one arising from the mean free path, the other from the collisions and these would be o opposite signs."

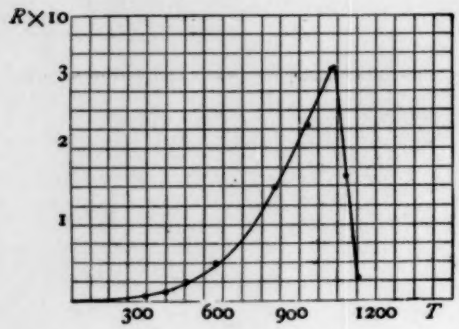

Fig. 22. Electrolytic iron.

If this be the correct explanation of the reversed effect in iron, it seemed that when the temperature of the iron had been raised to the critical temperature, the term in the Hall effect arising from the collision of electrons with magnetic molecules might be expected to drop out. If one assumes with Thomson only free negative electrons in the metal, the direction of the Hall effect arising from the action of the magnetic field on the electrons while they are moving over their free paths must be the same in all metals. According to this theory the Hall effect might be expected to

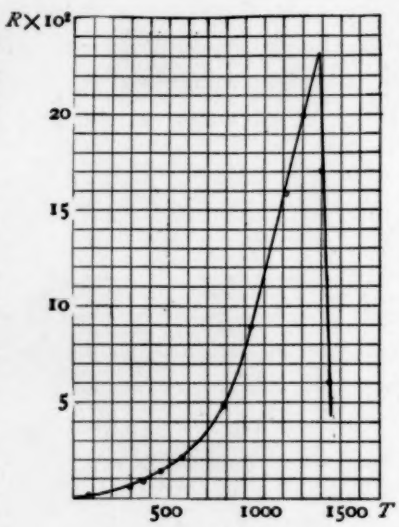

Fig. 23. Cobalt.

change sign at some temperature above the critical temperature and to have the direction of the effect in bismuth. From Fig. 21 it is evident that, although there is a sudden change in the magnitude of the effect in passing through the critical temperature, there is no indication of a change in the direction of the effect. The permeability of iron at 1000° C. is of the order of magnitude of 1.2. It seems that any term in the Hall effect depending on the magnetic properties of the iron ought to have nearly dropped out at that temperature. After passing the critical temperature a few degrees the influence of temperature on the effect in iron is of the same nature as its influence in the non-magnetic metals and there is no better reason for expecting a change of sign in iron with further rise of temperature than in a non-magnetic metal like platinum or copper. In view of the behavior of iron at temperatures above the critical temperature it does not seem probable that this explanation can account for the reversed effect in iron.

The effect in cobalt behaves in essentially the same way as the effect in iron but, for the reasons given above, observations were not made at temperatures as far above the critical temperature as in the case of iron, so that the conclusions for cobalt are less certain than they are for iron.

Summary.

The chief results of this paper are:

1. The temperature coefficient of the Hall effect in gold, zinc, platinum, silver and aluminum has for the first time been determined with certainty and it has been found that with the exception of aluminum there is in each of these cases a decrease in the effect as the temperature is raised from — 190° to about 22°. In the case of aluminum there is an increase, instead of a decrease.

2. The Hall electromotive force in each of these metals at the temperature of liquid air has been found to be proportional to the magnetic field.

3. The Hall effect in silicon has been found to have sometimes the direction of the effect in iron and sometimes the direction of the effect in bismuth. The purer specimens gave the effect in the direction of that in iron.

4. A reversal of the thermo-electromotive force in silicon has been found to be associated with a reversal of the Hall effect.

5. The Hall electromotive force in silicon has been shown to be proportional to the magnetic field.

6. The relation between the Hall electromotive force and the magnetic field has been examined in iron, nickel and cobalt for a number of temperatures between — 190° and 1100° C. For a given magnetic field the Hall effect in these metals has been found to increase with rising temperature until the critical temperature of the metal in question has been reached. The rate of increase becomes the greater the nearer the critical temperature is approached. In passing the critical temperature the effect sinks rapidly to a small fraction of its original value and then in the case of iron and nickel, and probably in cobalt, decreases slowly with further rise of temperature.

7. In the magnetic metals for any particular temperature the Hall electromotive force is proportional to the magnetic field, until the maximum intensity of magnetization in the plate has been reached. After this condition which has been called saturation has been reached, the curves showing the relation between the Hall electromotive force and the magnetic fields are nearly parallel to the axis of magnetic fields.

8. With increasing temperature the fields necessary to produce saturation become less in nickel and iron. In cobalt, however, the fields for saturation become greater with rising temperature until 300° is reached and with further rise of temperature the fields for saturation become less.

9. In nickel, iron and cobalt at temperatures a few degrees above the critical temperature the Hall electromotive force is proportional to the magnetic field over its range in these experiments.

10. It has been pointed out that the explanation of Thomson for the reversal of the Hall effect in iron is improbable in view of the fact that the effect in iron does not reverse sign at temperatures above the critical temperature where it has lost nearly all of its magnetic properties.

A similar investigation of several series of alloys is already in progress and the results will be presented in a subsequent paper.

PHYSICAL LABORATORY OF UNIVERSITY OF WISCONSIN,
July 19, 1909.

ON THE PENETRATING RADIATION AT THE SURFACE OF THE EARTH.[1]

By G. A. Cline.

1. Introduction.

During the last few years a number of investigators have made a study of the penetrating radiation which is known to be present at the surface of the earth with a view to locating its source or origin. The presence of radioactive substances in the soil and of radioactive emanations in the atmosphere suggest both the earth and the atmosphere as sources for part at least of this radiation. It is possible too for such a penetrating radiation as that present at the earth to have its origin in the sun or other celestial bodies.

It is known besides that the amount of radioactive emanation present in the atmosphere at any time is largely dependent upon the barometric changes which have taken place for a short time previously, and upon the precipitation which has occurred recently in the locality concerned. If then the penetrating radiation comes largely from the atmosphere it would follow from the above considerations that frequent though perhaps irregular changes should occur in the intensity of the radiation at any particular locality.

If the sun, however, contributed the major portion of the penetrating radiation we should then expect to find regular daily variations in its intensity. On the other hand if the greater part of the penetrating radiation has its origin in radioactive substances in the soil and rocks, we should expect to find but little, if any, variation in its intensity throughout the day or even from day to day in any particular region.

One of the first to note a diurnal change in the ionization of air contained in closed metallic cylinders was J. J. Borgmann.[2] His

[1] Communicated by Professor J. C. McLennan, and read before the Royal Society of Canada on May 26, 1909.

[2] Science Abstracts, 1905, No. 1580.

experiments were carried out in the neighborhood of St. Petersburg. Among other results he found that the ionization of the air in cylinders of copper, aluminium, brass, iron, zinc, tin, or lead, increased for some days after being enclosed, and finally reached a limit. This limit he found to vary from day to day and even during a single day. The minimum of conductivity noted by him was most frequently observed about three o'clock p. m.

Mach and Rimmer [1] while investigating the emanation content of the atmosphere at Vienna also made some measurements on the ionization of air confined in closed metallic vessels and from their measurements they were led to conclude that the penetrating radiation was more intense in the mornings and in the evenings than at noonday.

Amongst others Wood and Campbell,[2] at Cambridge, England, made an extensive examination of the penetrating radiation for a daily variation. In their experiments they made measurements on the ionization in different gases contained in closed metallic vessels of 6,000 c.c. capacity, and they used a sensitive quadrant electrometer as the measuring instrument.

From their experiments they showed that a periodic variation occurred in the ionization of the enclosed gases having two maxima and two minima each twenty-four hours. They also showed that the periodic variation was independent of the nature of the enclosed gas, and that the periodicity was independent of the metal of which the enclosing receiver was made. Their ionization curves representing these periodic changes were found too to be approximately the same as the curves representing the variations of atmospheric potential. As to the magnitude of the changes noted these experimenters found on the average that the variations in the ionization which took place in any one day amounted to about 12 per cent. of the whole.

McKeon,[3] of Washington, U. S. A., made an attempt to study the radiation by examining the variations in the potential assumed by an insulated metal cylinder placed within and completely sur-

[1] Phys. Zeit., 7, p. 617, Sept. 15, 1906.
[2] Phil. Mag., Feb., 1907.
[3] PHYS. REV., 1907.

rounded by a second metallic cylinder 120 cm. long and 20 cm. in diameter. In his observations he noted a double daily variation in the potential of the insulated cylinder. The effect measured in his experiments, however, does not appear to be exclusively dependent upon the intensity of the penetrating radiation.

Strong,[1] of Baltimore, also made a study of this penetrating radiation using a small enclosed gold-leaf electroscope as the measuring instrument. In his experiments he observed the loss of charge from this instrument in a variety of places including (1) a room in the Physical Laboratory at Johns Hopkins University, (2) a cistern filled with rain water, the electroscope being placed at the center and (3) a room in the open country in the State of Pennsylvania near Mechanicsburg. Strong from his measurements drew the conclusion that the atmosphere contributed by far the major portion of the penetrating radiation. He found the intensity of the radiation greater in summer than in winter, and he too noted a double diurnal period in the ionization in his electroscope. Precipitation of rain or snow always produced a drop in the intensity of the radiation. But all changes in intensity were eliminated when he surrounded his electroscope with thick lead and iron screens. Strong's measurements are rather remarkable for the extremely wide variations which they indicated and it is difficult to account for them. On January 30, 1907, for example, he observed ionizations at various times of the day represented by 12, 82, 100, 77, on an arbitrary scale, and again on September 3, 1909, ionizations were observed represented by 25, 18, 50 and 155, 150, 42, 10, 15 on the same scale. Variations so extensive as these do not appear to have been observed by any other investigators and they seem to point to some very special and exceptional local conditions.

Some experiments were also made recently on this phenomenon by D. Pacini, at Sestola, in Italy.[2] This investigator used an aluminium-leaf electroscope and studied the ionization in air enclosed in large zinc receivers. He too found daily maxima and minima values in the ionization. His minimum observations ranged from 8, 9, 10 to 12 ions per c.c. per second while his maximum observa-

[1] PHYS. REV., July, 1908.

[2] Rend. Acc. Lincei, 18, 123–129, 1909.

tions extended in some cases to as high as 30 ions per c.c. per second. His ionization values present a double daily period with two maxima at two to three o'clock and nine to ten o'clock, and two minima from seven to eight o'clock and from twelve to one o'clock.

Wulf[1] too who devised a new type of electrometer, the movable system of which consists of a double conducting quartz thread, has applied this instrument also to the investigation of the penetrating radiation. His experiments were carried out at Valkenburg in Holland, both on the surface of the earth and in the chalk quarries in the neighborhood of that municipality. He too found a parallelism between the intensity of the penetrating radiation and that of the atmospheric potential, maximum values being obtained for both phenomena in the summer about eight or nine in the morning and evening and minima about noon and midnight. In winter the midday minimum was only slightly marked.

The amplitude of the morning variations was found to be about 16 per cent., while that of the afternoon ones was about 10 per cent. of the total ionization. The mean ionization corresponded to from 25 to 30 ions per c.c. per second. The ionizations observed in the measurements in the chalk quarries were found to be only about 42 per cent. of those obtained on the surface of the ground.

In this connection it will be recalled that Elster and Geitel[2] observed a fall of 28 per cent. in the conductivity of air enclosed in an aluminium receiver when the apparatus was taken from the surface down to the bottom of a rock salt mine. It will be remembered too that C. S. Wright in his experiments at Toronto found the conductivity of air confined in closed metallic vessels in experiments on the ice of Lake Ontario to be about 46 per cent. less than in similar ones made on the lawn in the neighborhood of the physical laboratory. It will be recalled too that the ionization values obtained by Wright on the sand bars on the island near Toronto were but slightly higher than those obtained by him on the ice. The experiments at Toronto coupled with those at Valkenburg, and with those of Elster and Geitel, would seem to show that the earth and not the atmosphere is the source of the penetrating radiation and that certain

[1] Phys. Zeit., 10, 1909, 152–157.
[2] Phys. Zeit., No. 1, 1905, p. 733.

waters, soils and salt deposits are comparatively free from radioactive substances, and can therefore act as efficient screens. It also seems evident from these experiments that the penetrating radiation, in some localities at least, does not come from a very great depth in the earth's crust.

The experiments made at Sestola, however, seem to point to the atmosphere as the source of the radiation.

By an inspection of the data furnished it will be seen that very little connection exists between the times of the maxima and minima obtained in the different localities mentioned. It seems evident, too, after surveying all the recorded observations that the variations noted must be ascribed to changes in atmospheric conditions rather than to solar influences. No such regularity occurs in the variations as one should expect if the penetrating radiation had its origin in the sun.

In the course of his experiments at Toronto, C. S. Wright on several occasions made observations on the conductivity of air enclosed in metallic receivers over periods of time extending in some cases up to six or seven hours. Two typical sets of observations are given in the following table and from the readings recorded

TABLE I.

Time.		q_0=Number of Ions per c.c. per sec. Reduced to 0° C.
December 24, 1907.	10:23 a. m.	22.48
	10:43	22.51
	11:10	22.54
	11:32	22.45
	11:55	21.74
	12:15 p. m.	22.73
	12:40	21.96
	1:00	22.94
December 26, 1907.	9:35 a. m.	22.44
	9:58	21.86
	10:20	21.87
	10:45	22.25
	11:05	22.96
	11:28	22.79
	11:50	22.53
	3:55 p. m.	22.65
	4:15	22.54
	4:40	22.94
	Mean	22.45

it will be seen that there is no evidence of any appreciable regular variation in conductivity, and it is to be noted also that the extreme values obtained for the conductivity did not differ from the mean by more than 3 per cent. of the latter.

It would seem from these observations, therefore, that very little diurnal variation exists in the penetrating radiation at Toronto. Wright's observations, however, were extremely limited in number and it was decided to extend them, in order to ascertain whether it would be necessary to modify in any way the conclusions which might be drawn from them. The following paper contains an account of these observations and it will seen from the results that they point quite definitely to the absence of any regular diurnal variations.

2. Apparatus.

The measuring instrument used was the latest type of Wilson gold-leaf electroscope, and the arrangement of apparatus adopted is shown in Fig. 1. The case of the electroscope was joined to earth and the leaf system to an electrode which passed up into the ionizing chamber R. This chamber was insulated from the electroscope case, and could be charged as desired by means of the battery B to any selected potential. Attached also to the leaf system was the inner tube of the sliding condenser C, for details of which the reader is referred to the paper by C. S. Wright mentioned above. In the measurements to be described the receiver was charged negatively to about 180 volts, which was found sufficient to insure a saturation current. The small quartz Leyden jar Q was kept at a negative potential of approximately 50 volts, and the slide tube

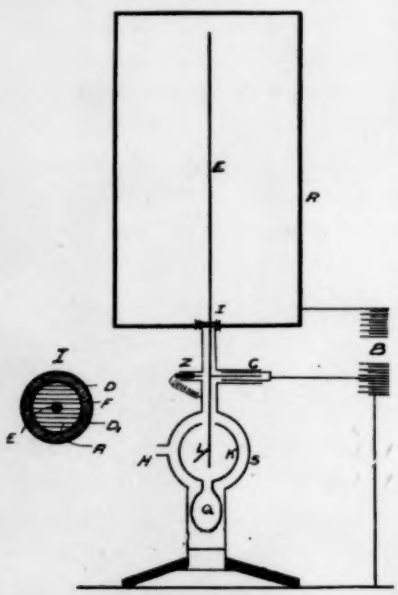

Fig. 1.

condenser C at varying negative voltages depending on the sensibility desired.

By moving this condenser any charge acquired by the gold leaf system through the conductivity of the air enclosed in R could be annulled. In the experiments the condenser was always moved over a standard distance and the time was taken for the conduction current to annul the deflection of the gold leaf produced by the displacement of the sliding condenser.

The charge annulled per unit voltage applied to the compensator tube was .00501 e.s.u., a number which was determined by using the auxiliary parallel plate condenser supplied with the instrument.

Assuming the charge carried by an ion to be 3.4×10^{-10} e.s.u., it follows when the volume of the receiver is known and also the time required for the conduction current to annul a given quantity of electricity, that the number of ions per c.c. per second "q" in the receiver R can be readily found.

3. Experiments, Series I.

In this series of experiments the receiver R was made of sheet zinc. The potentials used were obtained from a set of small dry cells which remained constant over the whole range of measurements.

The receiver R, whose capacity was 31,180 c.c., was kept at a constant potential of 184.5 volts, throughout, the Leyden jar Q at 51.5 volts and the sliding condenser C at 13.2 volts. In this series of measurements the receiver was not hermetically sealed, so that barometric changes were necessarily followed by changes in the air content of the receiver.

The readings were taken visually and were commenced by a few preliminary observations over periods of from four to six hours' duration selected from different parts of the day. These were afterwards followed by observations taken continuously over a twenty-four hour period.

In the measurements for the shorter periods the apparatus was set up in a room in the Physical Laboratory and rested on a solid stone table which constituted the sill of one of the windows in the room.

The first observations were taken during the evening of November 25, 1908, and are shown in Fig. 2. During the readings the barometer was practically stationary and stood at 753 mm. The mean

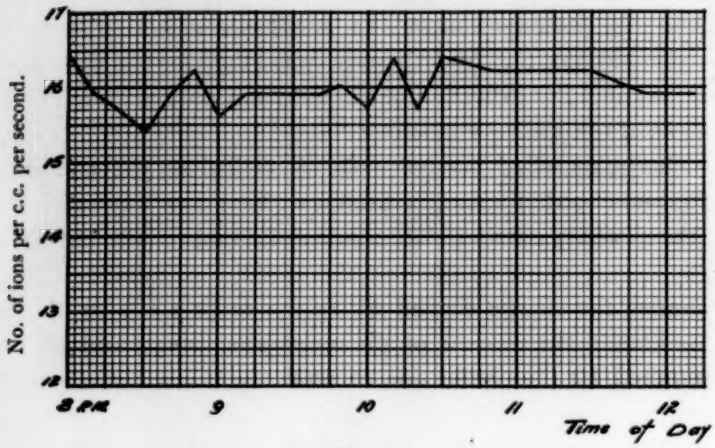

Fig. 2.
November 25, 1908; barometer, 753.

value of the readings it will be seen was 15.95 ions. In no case was there a deviation from the mean value of greater than 3 per cent., and the curve shows no evidence of any marked variations which might be ascribed to changes in the radiations which contributed to the conductivity of the enclosed air.

Similar sets of observations were taken on the afternoon and even-

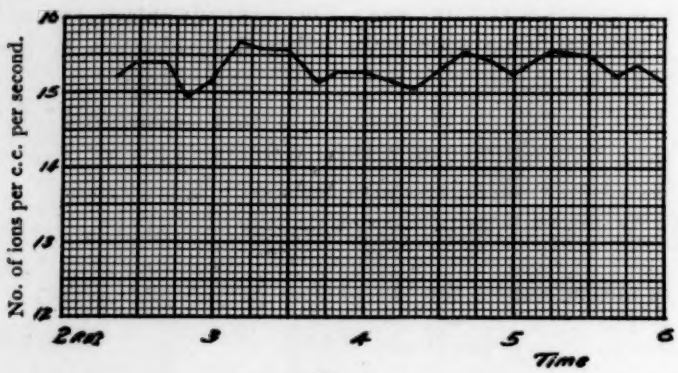

Fig. 3.
November 27, 1908; barometer, 760.

ing of November 27, 1908, and are illustrated by the curves shown in Figs. 3 and 4. Here again it will be seen that the extreme deviation from the mean value did not exceed 3.5 per cent. More-

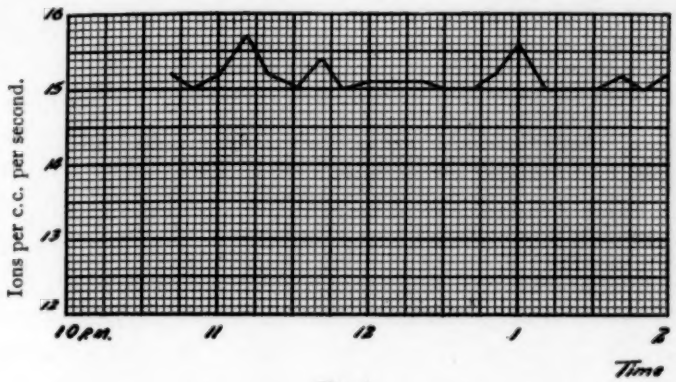

Fig. 4.
November 27 and 28, 1908; barometer, 762.4.

over, the variations which did occur represent practically the limits of accuracy with which the readings could be taken by the measuring instrument.

Again, sets of observations were taken on the afternoons of December 3, 4 and 7, the results being shown in Figs. 5, 6 and 7.

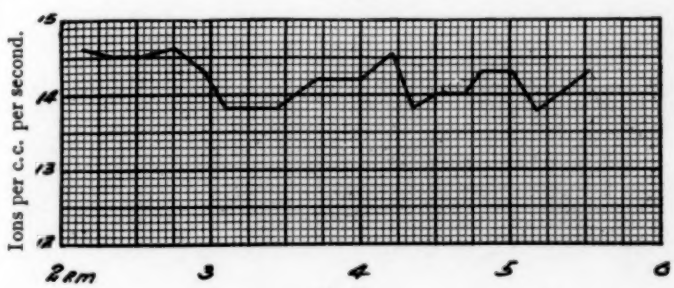

Fig. 5.
December 3, 1908; barometer, 762.5 to 761.6.

From these it will be seen that in one case the deviations from the mean were not greater than 1.5 per cent., while in the other two they did not exceed 3 per cent.

Further the curves shown in Figs. 2, 3, 4, 5, 6 and 7 indicate, it will be seen, but little variation during the periods of taking the readings. The readings from day to day, however, showed con-

siderable variation but these were no doubt due to variations in the amount of radioactive emanation present in the atmosphere. As the receiver was not hermetically sealed the free interchange of air which this condition permitted could easily account for the differences noted.

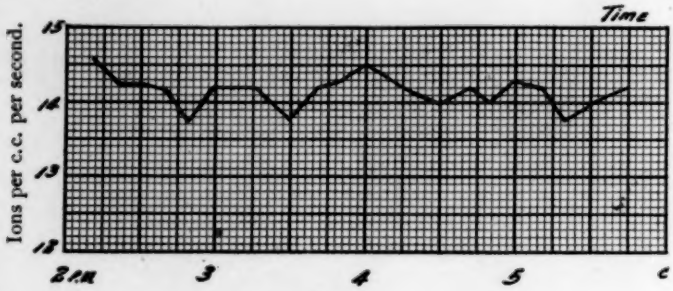

Fig. 6.
December 4, 1908; barometer, 747.2.

A point of interest in connection with these observations and one which has been observed by other investigators was that the ionization was greater when the barometric pressure was low than when it was high. A falling barometer would promote the effusion of gases occluded in the soil, and this process of effusion would consequently result in an increase in the amount of emanation present in the air and so account for the higher conductivity.

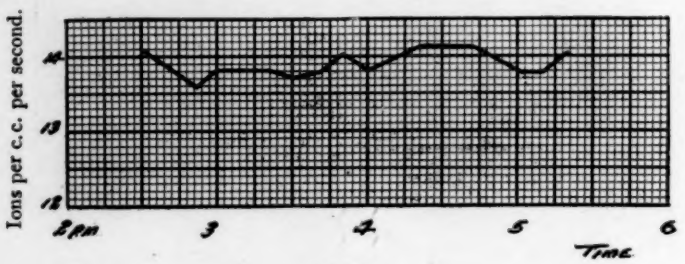

Fig. 7.
December 7, 1908; barometer, 747.7.

It was also noted in these experiments that the conductivity of the air in the cylinder was less for corresponding barometric pressures when the ground was frozen and covered with snow than when the temperature was above freezing point and the ground bare.

After completing the preliminary series of measurements just described it was decided to undertake a series extending over a twenty-four hour period. The readings were taken on December 18 and 19, 1908, in the library of the Physical Laboratory. This was a large well ventilated room facing the southeast and in it the apparatus was set up on a table close to one of the windows. During this set of observations the barometer remained fairly steady, the maximum change being from 746.3 to 749.5. The readings are shown in Fig. 8.

From an inspection of these readings and the curve, it will be seen that there is no evidence of a regular diurnal variation in the ionization. The extreme deviations in the readings from the mean

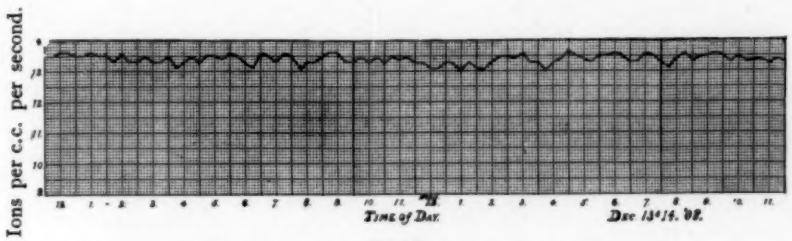

Fig. 8.
Open zinc receiver.

taken throughout the whole period were not greater than 3 per cent., and as the instrument could not be used under the conditions of the experiment to give a greater accuracy than 2 or 3 per cent. one is forced to conclude from these observations that at Toronto there are no daily variations in the intensity of the penetrating radiation greater in magnitude than such variations as came within the limits of sensibility of the measuring apparatus.

In the experiments which have been described no special precautions were taken to have the cylinder hermetically sealed. At a number of joints minute openings were left unclosed and so there must necessarily have been a constant interchange between the air inside the cylinder and that outside. It is worthy of note to observe that even with this interchange only very small variations in the conductivity of the air occurred during the twenty-four hour period.

4. EXPERIMENTS, SERIES II.

In order to submit the question of a diurnal change in the intensity of the penetrating radiation to a further test a second set of readings was taken over a period of twenty-four hours. In these a cylinder of galvanized iron was used of capacity 29,950 c.c. The electrode in this case was divided into sections, the one portion extending from the gold leaf to the top of the electroscope and the other being supported by insulating materials in position in the cylinder. The insulated electrode in the receiver was protected by an earthed guard tube which was also sealed in position and finally all the joints of the cylinder were made air tight by means of either solder or marine glue.

When the cylinder was placed in position above the electroscope a small spring made metallic contact between the two sections of the electrode.

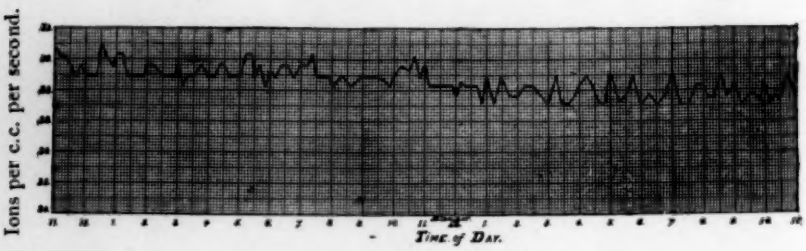

Fig. 9.
Closed galvanized iron receiver.

A small glass U-tube mercury manometer was also sealed into the side of the receiver to give indication of any air leak in the vessel.

In preparing for the observations care was taken to thoroughly clean the inside of the receiver and freshly filtered air was introduced into it to a pressure slightly greater than atmospheric pressure. This slight excess of the inside pressure over that of the atmosphere outside produced a difference of level in the two arms of the manometer. From the manner in which this difference of level followed the changes in the barometer it was soon seen that the receiver was airtight, and therefore in the condition desired for the observations.

When this point was made certain the readings were commenced.

These were taken on December 18 and 19, 1908, and are shown in Fig. 9.

This curve also, it will be seen, shows no regular periodic variation. Further the greatest deviation from the mean value was not more than 4 per cent. The capacity of the measuring system was greater in this set of measurements than in the previous one but the same voltage was applied to the sliding condenser as in the previous measurements. The result of this change was to reduce the sensibility of the apparatus slightly and this would account for the 4 per cent. variations in the readings apart altogether from any variation in the conductivity.

A point of special interest in connection with the readings is the gradual drop which they indicate in the conductivity of the enclosed air. This drop, which has been observed by others in similar measurements, was no doubt due to the gradual removal by the field of the suspension particles designated by Langevin [1] as "large ions" and first investigated by him. When the air was introduced into the receiver it was passed through a tube filled with cotton wool. This filter it was thought would remove all the dust and fine particles in suspension, but it was found after the completion of the measurements that when air filtered in the same way was led into an expansion cloud chamber of the C. T. R. Wilson type that it still contained suspension particles in abundance which acted as cloud nuclei. During these measurements the barometer only changed from 744 to 752 mm.

On account of the higher radioactivity possessed by the walls of this receiver the conductivity of the air in this case was about double its value in the early measurements. This enabled the writer to take a greater number of observations in a given time, but on account of the failure to increase the voltage of the condenser tube it did not contribute anything to the sensitiveness with which the readings were taken.

5. Experiments, Series III.

The experiments which have been described up to the present were all conducted indoors and as the walls of the physics building

[1] Comptes Rendus, 140, pp. 232, 1905.

very probably reduced in some degree the intensity of the penetrating radiation it was thought best to complete the series of observations by placing the receiver of the apparatus outside and so exposed directly to the atmosphere.

To accomplish this the electroscope was taken to the attic of the building and set up beneath a small opening in the roof. The receiver was placed on the roof over this opening on insulating supports and the electrode which it carried was joined to that of the leaf system by the insertion of a light metal rod 1⅔ meters in length. A guard tube was also added to protect this added length to the electrode.

In setting up the apparatus this time a lining of thick sheet zinc was inserted which had been carefully abraded with fine glass paper and then thoroughly washed in turn with dilute hydrochloric acid, ammonia, methyl alcohol and distilled water. Fresh filtered air was drawn into the receiver and it was then hermetically sealed. Readings were taken immediately afterwards. In this case also it was noticed that the conductivity of the air gradually decreased and ultimately assumed a steady value. In the initial measurements the conductivity corresponded to as high as 19 ions per c.c. per second, but in the steady state it approximated to the generation of only 11.0 ions per c.c. per second.

This low value illustrates the great differences which exist in the radioactivity of different metals. With the galvanized iron cylinder alone it will be remembered that the conductivity corresponded to the production of about 35 ions per c.c. per second. The insertion of the zinc lining, it will be seen, therefore cut off by far the greater portion of the radiation from the galvanized iron. The reduction in the conductivity of the enclosed air necessarily made that portion contributed by the penetrating radiation of greater relative importance and it was thought that a more severe test would thus be available for the detection of diurnal variations. It was found however that the insertion of the long electrode greatly reduced the sensibility of the electroscope. By the addition of this the capacity of the instrument was nearly trebled, and consequently, although the displacement of the gold leaf for a given movement of the condenser tube could be increased by adding to the voltage of the latter

still this device had the defect of adding to the time of taking a reading, and as it was desirable to have the readings taken as frequently as possible it was found necessary, therefore, to apply only a moderate voltage to the condenser. For this purpose a potential of 21 volts was maintained on the condenser tube, and this permitted readings to be taken, though with diminished accuracy, every 15 or 20 minutes.

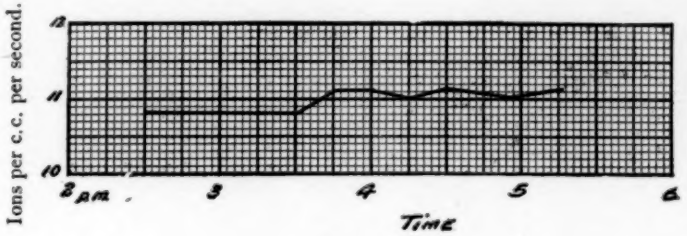

Fig. 10.
March 15.

With the apparatus set up in the manner just described sets of readings were taken during the afternoons of March 15, 22 and 26, 1909, the results being shown in Figs. 10, 11 and 12.

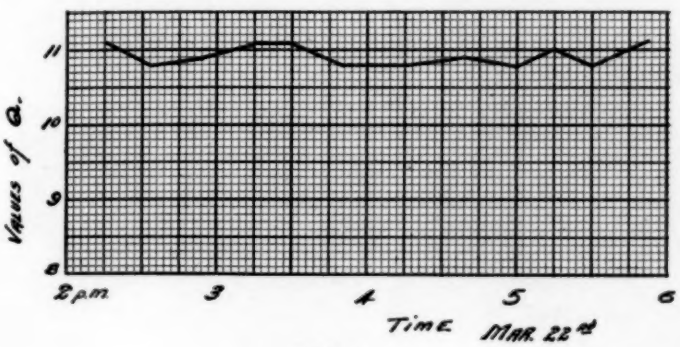

Fig. 11.

The readings for the three afternoons, it will be seen, approximated to 11 ions per c.c. per second.

By comparing the three curves it will be seen that although the readings were not uniformly regular still no periodic daily variation was brought into evidence. On March 28 and 29 and again on April 4 and 5, 1909, readings were again taken with this apparatus continuously over periods of twenty-four hours, as shown in Figs.

13 and 14. These readings it will be seen are far from being so uniform as those of the earlier observations. The variations from the mean it will be seen are very considerable, and are attributable,

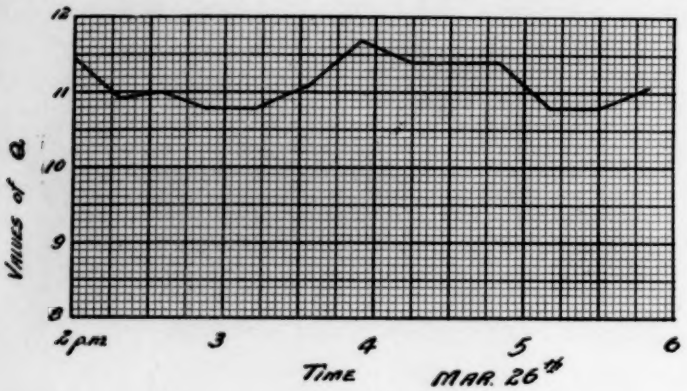

Fig. 12.

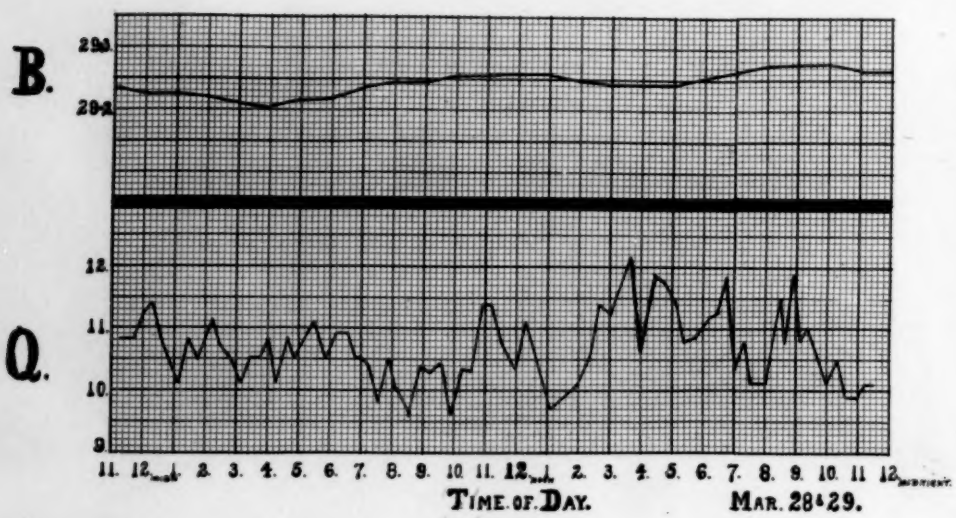

Fig. 13.

in the judgment of the writer, to the lack of sensitiveness in the instrument and the consequent difficulty in taking the readings, rather than to any variations in external influences.

In Fig. 13 the barometric curve is drawn for the corresponding twenty-four hour period. From an inspection of the two curves there does not appear to be any connection between the changes in

conductivity and the changes in atmospheric pressure as indicated by the barometric readings.

In order to see whether a combination of the curves shown in Figs. 13 and 14 would give any indication of a pronounced maximum

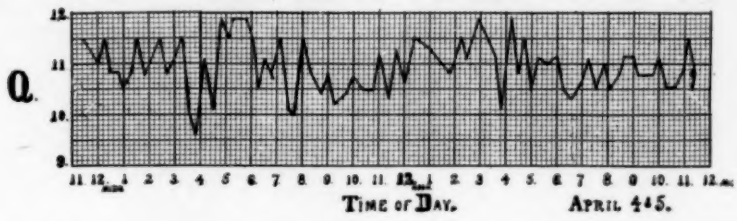

Fig. 14.

and minimum conductivity the two curves were compounded by taking the mean of the readings for the same time of the day. The individual curves are shown overlapping in the upper portion of Fig. 15, and the compound curve is shown at the bottom of the same

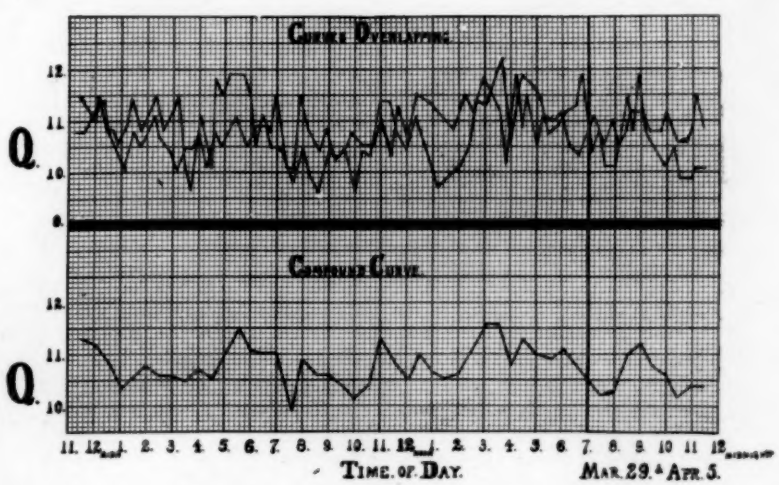

Fig. 15.

figure. From the figure, however, it is impossible to draw the conclusion that any maximum or minimum conductivity was associated with any particular hours of the day.

While the lack of sensibility in the measuring instruments prevented these later observations from leading to as satisfactory conclusions as might be desirable, still they agree with the earlier ones in failing to point to any variation of a regular diurnal character,

and in this they seem to show that the conditions at Toronto are somewhat different from those which prevail in a number of other localities where similar observations have been made.

The writer had hoped to continue the investigation out in the open country with the electroscope arranged as adjusted for maximum sensibility, and possibly too with auxiliary apparatus attached for taking the readings automatically in place of taking them visually, but time has not permitted and the further investigation of this point has been of necessity deferred.

6. SUMMARY.

In summarizing the results of the investigation the following are the chief points which have been noted.

(*a*) With an open receiver. (1) No daily regular maxima or minima conductivities were observed. (2) Changes in conductivity occurred from day to day which seemed to be directly connected with concurrent barometric changes. (3) The conductivity was found to be slightly less when the ground was frozen and covered with snow, than when it was bare and the temperature was above freezing point.

(*b*) With a closed receiver. (1) Larger variations in the conductivity were observed but no regular diurnal maxima or minima values were noted. The larger variations in the conductivity were attributed to a lack in the sensitiveness of the measuring electroscope. (2) Different metals which were used in the construction of the receiver were found to possess different activities, zinc being very low. (3) Atmospheric air even when well filtered through cotton wool was found to contain many suspension particles.

As a general result of the investigation it would appear that the soil contributes by far the greater proportion of the penetrating radiation present at the earth's surface at Toronto and, by comparison, any that may have its source in the atmosphere or in the sun may be considered to be negligible in amount.

In closing I wish to express my gratitude to Professor McLennan for his kindness throughout the research, for suggestions and for assistance in overcoming mechanical difficulties. My best thanks are also due Mr. E. F. Burton for his kindness in taking a number of the readings.

THE VARIATION WITH VELOCITY OF e/m FOR CATHODE RAYS.

By C. A. Proctor.

THE experimental investigation of the variation with velocity of electromagnetic mass has been carried out with great care by Kaufmann [1] and Bücherer [2] with the aid of the β rays from radium. The conclusions from these two researches are not in accord, and while the weight of evidence since the recent publication of Bücherer's results is certainly on the side of the Lorentz-Einstein rather than that of the Abraham theory, it is important that these results should be checked by different observers and different methods. There are two reasons at least why it appears the best check would be furnished by measurements on cathode rays in a very high vacuum. The range of velocities covered by the β rays is from about four to nine tenths of the velocity of light. Experiments with cathode rays would cover quite a different range — probably from about one to six tenths of the velocity of light. Furthermore a series of simultaneous measurements of discharge potentials, electric deflection and magnetic deflection furnishes a double check on the accuracy of the theoretical formulæ, since the longitudinal as well as the transverse inertia of the electrons here comes into play. This phase of the question has been discussed in some detail by Planck.[3] It is in this respect that the discharge tube has a distinct advantage over radium rays, since in observations upon the latter the only quantities measured are the two deflections and in consequence the transverse mass alone is involved.

Such a series of measurements has been carried out by H. Starke,[4] but the range of potentials was too small or the experimental error

[1] Kaufmann, Ann. d. Phys., 19, p. 487, 1906.
[2] Bücherer, Ann. d. Phys., 29, p. 589, 1909.
[3] Planck, Verh. der D. Phys. Ges., 8, p. 418, 1906.
[4] Starke, Verh. der D. Phys. Ges., 8, p. 418, 1906.

too large for the results to be of value as evidence in favor of one theory or the other. The work of Classen [1] and Besthemeyer [2] also touches upon this question, but in neither case does the experimenter consider that any conclusive results have been reached.

It was in the hope of obtaining measurements over a sufficient range and of sufficient accuracy to be admissible as evidence on this matter that the work about to be described was undertaken. The results so far obtained are based on measurements of the two deflections alone, and cover a range of velocities only from twelve to forty-three hundredths of the velocity of light. Nevertheless they seem to be of sufficient interest to warrant their publication at this time especially as they are in much closer agreement with the Abraham than with the Lorentz theory.

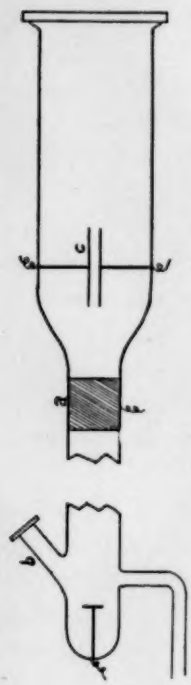

Fig. 1.

That the discharge in a cathode tube may take place in the highest possible vacuum, whatever the discharge potential, a condition clearly desirable if not essential, it is necessary to excite it by external means. Two such means suggest themselves — ultra-violet light and the Wehnelt cathode. The former was tried by the writer. The discharge tube was provided with a short branch (*b*), Fig. 1, closed by a quartz window. Through this window the aluminum cathode was illuminated by a powerful oscillatory spark between zinc electrodes. While this spark was rich in ultra-violet light the discharge produced by it was insufficient to cause the screen in the tube to fluoresce even at high discharge potentials. Careful cleaning of the cathode and modifications of the spark circuit failed to change this condition. In view of the results obtained by Lenard this was most surprising, and the writer has been entirely at a loss to account for it. In subsequent work a Wehnelt cathode will be employed as experiment shows that there

[1] Classen, Verh. der D. Phys. Ges.

[2] Besthemeyer, Ann. d. Phys., 22, p. 429, 1907.

is no difficulty in obtaining a sufficient discharge from it. In the measurements so far made the potential was controlled largely by the degree of vacuum in the tube. The effect of this on the results will be considered later.

To obtain potential measurements of sufficient accuracy to be of any value, a voltometer which can be read quickly and whose readings can be relied on to a fraction of one per cent. is essential. None of the various arrangements of apparatus so far tried by the writer has met these requirements at high potentials, so that only readings of magnetic and electric deflections have as yet been obtained. A new voltometer of the general design of that used by Müller [1] is now under construction in the shop of Ryerson laboratory. Judging by Müller's results this should meet the needs of the experiment.

The arrangement of the discharge tube is shown in the accompanying sketch. The anode (Fig. 1) is a brass cylinder closed at one end except for a slit 0.5 mm. wide and 1.5 cm. long. The condenser (c) consists of two brass plates 4.2 × 2.4 cm. and 0.47 cm. apart. The end of the tube opposite the cathode is closed by a piece of plate glass coated on the inner side with calcium tungstate and cemented on.

The length of the condenser, distance from anode to screen, and distance from condenser to screen which enter into the computation of the electric field integral were measured with a steel scale graduated in hundredths of an inch. The distance between the condenser plates was measured by means of a cathetometer. From the dimensions so obtained the electric field integral

$$\int_a^{\infty}\int_a^{\infty} F dx \cdot dx$$

was computed with the aid of Maxwell's formula. The value obtained was held under suspicion, however, as the proximity of the walls of the tube, shielded by grounded tinfoil, to the end of the condenser next the anode rendered questionable the applicability of the formula. This suspicion was confirmed by the fact that the values of e/m at low velocities computed from this value of the field integral

[1] Ann. d. Phys. (28), 3, p. 591, 1909.

were impossibly large. It was accordingly thought best to determine this quantity as follows. A series of forty readings were taken of the magnetic deflection and discharge potential at about 8,000 volts. At this value the potential, furnished by a twenty-four plate static machine, could be held very constant and measured with considerable accuracy with a Braun 10,000-volt electrometer. From these readings the values of e/m and the velocity were obtained in the usual way and the value of e/m for zero velocity computed with the aid of the Abraham formula. The value obtained was 1.859×10^7. This agrees within the limits of experimental error with that of Simon [1] but not with the more recently published results of Classen, Besthemeyer and Bücherer. It should be noted however that a very considerable change in this value would not appreciably affect the conclusions regarding relative values of e/m at different velocities. From this value of e/m and a series of readings of the electric and magnetic deflections also taken at discharge potentials of about 8,000 volts the value of the electric field integral was computed. The value thus obtained was about 10 per cent. less than that given by Maxwell's formula and was used in all subsequent computations. The justification for this method of determining the field integral is found in the work of Seitz,[2] who has shown that it is correct at the potentials here employed.

The magnetic field was obtained by means of a solenoid 24 cm. in diameter made in two sections each 48 cm. long and separated by a gap of 3 cm. to allow of the introduction of the discharge tube. This was mounted with its axis east and west and the discharge tube was so placed that the undeflected rays cut this axis at right angles. As the discharge tube was horizontal there was a considerable lateral deflection of the rays at low potentials due to the vertical component of the earth's field. This was compensated by a large horizontal coil immediately beneath the tube. The form of the magnetic field, proper position of the tube with reference to the solenoid, and correction for finite curvature of the magnetically deflected rays were determined by the methods given in detail by S. Simon.[3] The absolute value of the field on the axis of the solenoid

[1] S. Simon, Ann. d. Phys., 69, p. 589, 1899.
[2] W. Seitz, Ann. d. Phys., 8, p. 233, 1902.
[3] S. Simon, *l. c.*

was determined as follows: A magnetometer with a heavy phosphor-bronze suspension was mounted so that the magnet was on the axis of the solenoid where the field is sensibly uniform, and adjusted until the magnet was perpendicular to this axis. This condition was judged to be fulfilled when the deflections on opposite sides of the zero were the same for any current within the possible range. The mean deflection for a known current was then determined from ten separate readings. This work was then repeated substituting for the solenoid employed in the experiment another solenoid whose field could be computed from its known dimensions. This reference solenoid was made, and has been repeatedly used, for the determination of the absolute value of the ohm. As in that work it gives results correct to within 0.1 per cent. there can be no doubt that its computed field is very little in error. Currents were measured with an "American" ammeter which was calibrated throughout its range by comparison with a Kelvin balance whose accuracy had been recently checked with the silver voltameter. Two determinations of the field made as above with different magnetometers and widely different currents gave values differing by 0.3 per cent. and their mean was taken as the value of the field.

The potential difference in the plates of the condenser was obtained from a battery of small storage cells. The values used ranged from 70 to 800 volts. This potential was measured with a 320-volt Kelvin multicellular voltometer, calibrated by comparison with a 300-volt Weston direct current instrument. The Weston instrument itself was sent to the Bureau of Standards for calibration. A resistance of 10,000 ohms was placed in series with the battery and condenser. The potential was found to remain sensibly constant during any series of readings. Its value was therefore taken only at the beginning and end of each series and the mean used. These readings were commonly taken while the discharge was passing through the tube. Repeated tests showed, however, that the readings were the same when the discharge was not passing.

The general procedure in taking readings was as follows: The condenser potential and current in the solenoid were so adjusted that the deflection due to either was from one to two centimeters at the particular discharge potential employed. Readings of the electric

and magnetic deflections were then taken alternately until a series usually consisting of five of each was obtained. The deflections were measured with a cathetometer which could be set on the fluorescent spot with an error not greater than 0.02 mm. The current in the solenoid was read with each of the magnetic deflections. The means of the currents and of each set of deflections were then taken. Readings were taken in this way to eliminate as far as possible the effect of the unsteadiness in the discharge potential which could not be held perfectly constant. The variations were commonly of the order of 1 per cent. The deflection per ampere in the solenoid and per 100 volts difference of potential on the condenser were then computed.

Forty-four pairs of magnetic and electric deflections obtained as above were for comparison with the theoretical formulæ divided into ten groups according to magnitude and the mean of each group taken. From the magnetic deflections the value of e/m for zero velocity, and the constants of the apparatus, the electric deflections to be expected on the Lorentz-Einstein and the Abraham theories were computed.

The reduction of observations was made by this method for the sake of comparing results with those of Kaufmann, to whom it is due. The method is in brief as follows:

If z = magnetic deflection corrected for finite curvature,
y = electric deflection,
M = magnetic field integral,
E = electric field integral,
e = charge on electrons,
m = mass of electrons,
β = velocity of electron divided by velocity of light,
c = velocity of light,

we have from the ordinary theory

$$z = \frac{eM}{m\beta c^2},$$

$$y = \frac{eE}{m\beta^2 c^2}.$$

If we set $m = m_0\varphi(\beta)$ where m_0 is the mass of the electron at zero

velocity and $\varphi(\beta)$ expresses the dependence of mass upon velocity we have

$$z = \frac{e}{m^0}\frac{M}{c}\frac{1}{\beta\varphi(\beta)},$$

$$y = \frac{e}{m_0}\frac{E}{c^2}\frac{1}{\beta^2\varphi(\beta)}.$$

If we know e/m_0, z and the form of the function $\varphi(\beta)$ we can compute y. For the details of this computation the reader is referred to Kaufmann's paper. For the Lorentz-Einstein theory we have

$$\varphi(\beta) = (1 - \beta^2)^{-\frac{1}{2}}.^1$$

For the Abraham theory we have

$$\varphi(\beta) = \frac{3}{4}\frac{1}{\beta^2}\left\{\frac{1+\beta^2}{2\beta}\log\frac{1+\beta}{1-\beta} - 1\right\}.^1$$

Table I. shows the results of computation compared with observed deflections. There is close agreement between the writer's results

TABLE I.

β	Magnetic Defn.	Elect. Defn. Observed.	Elect. Defn. Lorentz.	Per Cent.	Elect. Defn. Abraham.	Per Cent.
.432	2.678	0.1467	0.1511	3.0	0.1486	1.3
.408	2.866	0.1665	0.1712	2.8	0.1686	1.2
.387	3.022	0.1849	0.1887	1.9	0.1862	0.7
.341	3.485	0.2423	0.2465	1.7	0.2438	0.6
.285	4.205	0.3499	0.3525	0.7	0.3499	0.0
.229	5.353	0.5545	0.5657	2.0	0.5614	1.2
.187	6.535	0.8306	0.8313	0.1	0.8296	−0.1
.157	7.857	1.188	1.195	0.6	1.194	0.5
.140	8.749	1.483	1.478	−0.3	1.476	−0.5
.123	10.043	1.932	1.943	0.6	1.943	0.6

and those of Kaufmann, the variations of computed from observed values being in the same direction in both cases and about twice as great for the Lorentz formula as for the Abraham. On the other hand, both are quite different from those given by the recent experiments of Bücherer, who finds complete agreement between experiment and

[1] Abraham, Theorie d. Elect., Vol. II., pp. 191 and 203.

the Lorentz formula. A careful consideration of possible sources of error fails to reveal any that could account for the large discrepancy between the results and those of Bücherer, unless it be the residual gas in the dischage tube. As the discharge potential was controlled to a large extent by the degree of vacuum in the tube there was a considerable amount of gas present at the lower potentials. As has been pointed out by J. J. Thomson and others it is a matter of uncertainty how much this may affect the values of e/m obtained. In his discussion of Kaufmann's results Planck[1] has shown that some modification of the theory of the experiment is necessary, as the value of the velocity of the electrons computed from the apparatus constants and the smallest deflections is greater than the velocity of light, and that they conform more nearly to the Lorentz than to the Abraham formula if the assumption is made that the electric field integral is modified by the presence of residual gas. An attempt to apply this to the writer's results leads to difficulty, for the effect in question is a reduction of the electric field integral and we should expect this reduction to increase with the amount of gas present. In the present work then this effect should be greatest at the low discharge potentials and diminish progressively as the potential increased. If we took account of this in computing the results the apparent variation of e/m with velocity would become smaller. As it is already too small to fit either theory it is evident that this explanation in its present form does not suffice.

Another method of exhibiting the results is shown in Table II. From the observed deflections and constants of the apparatus β and e/m are computed. These appear in columns one and two of the

TABLE II.

β	Magnetic Defn.	Elect. Defn. Lorentz.	Elect. Defn. Abraham.	β	Magnetic Defn.	Elect. Defn. Lorentz.	Elect. Defn. Abraham.
.432	1.738	1.927	1.886	.229	1.838	1.888	1.877
.408	1.755	1.922	1.885	.187	1.828	1.861	1.854
.387	1.757	1.905	1.873	.157	1.848	1.871	1.866
.341	1.783	1.896	1.872	.140	1.835	1.853	1.849
.285	1.796	1.875	1.858	.123	1.856	1.871	1.867

[1] Verh. d. El. Phys. Gesch., 9, p. 301, 1907.

table. From them are computed the value of e/m_0 by the Lorentz and by the Abraham formulæ. These are shown in columns three and four. If either formula exactly represented the observations e/m_0 should be constant. The values computed from the Abraham formula are perhaps constant to within the limits of observational errror, but those computed from the Lorentz formula certainly are not.

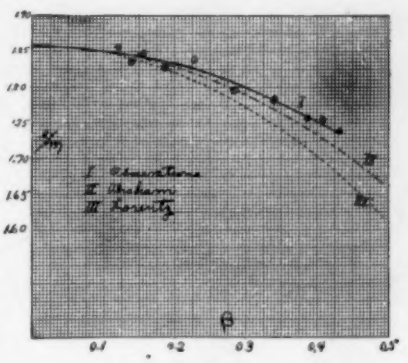

Fig. 2.

Fig. 2 shows the observed values of e/m as a function of β, and the values computed from the two formulæ in question.

In conclusion I wish to express my great indebtedness to Professor Millikan to whose suggestion this work is due, and who has during its progress been ever ready with friendly interest and helpful advice.

July 13, 1909.

THE FATIGUE OF METALS SUBJECTED TO THE ROENTGEN RADIATION.

BY R. C. GOWDY.

PROFESSOR L. T. MORE[1] has found that the secondary Roentgen radiation from metals is not independent of the duration of the exposure, but that the metals suffer a fatigue comparable to that produced by ultra-violet light.

His results show that the radiations from old surfaces of iron, lead, nickel and zinc, exposed to air, depend on the duration of the exposure, while the radiations from aluminium and copper are nearly constant.

Freshly polished surfaces of iron and lead show an initial rise in sensitiveness.

The effects when the metals are surrounded by an atmosphere of coal gas do not differ from those obtained in air. An inert gas, like hydrogen, seems to reduce the fatigue, while the presence of ozone increases it, though not in any way comparable to the extent noted by Hallwachs[2] for the ultra-violet radiation.

In conclusion the writer states that his results indicate that the fatigue is caused by "changes in the gas in or on the plates, rather than any changes in the metals themselves."

Following the suggestion of Professor More, this work has been carried on for the purpose of verifying his results and continuing the investigation, particular attention being given to the effect of oxidation on the behavior of the secondary radiation.

The first measurements of fatigue in this paper were made by the method described in the earlier paper by Professor More. A brief account of the method will be sufficient here. For more detailed description the reader is referred to the above mentioned work.

[1] More, Phil. Mag., XIII., 1907, p. 708.

[2] Hallwachs, Sitzungsber. der Ges. der Wissensch. zu Leipzig, LVIII., 1906, p. 341.

The Roentgen radiation is allowed to fall upon two similar plates, and their secondary radiations are measured and compared. If then one of these plates, which we will call the "standard," be shielded from the radiation, and the other, known as the "trial" plate, be exposed for a length of time, a second comparison of the radiations may be expected to show any change in sensitiveness of the "trial" plate, due to its prolonged exposure to the X-rays.

This method, being comparative, eliminates to a great extent the variations in the working of the coil and bulb from one set of observations to the next, but assumes that the primary radiation is constant or varies regularly during each particular set of measurements. Even with the most careful manipulation, irregularities in the action of the coil and bulb introduce considerable error, in some cases masking the effects sought.

If the radiation from both plates could be measured at the same time, and by the same instrument, the effect of the irregularities above noted would be nearly eliminated. A differential method was therefore devised, which accomplished practically this result.

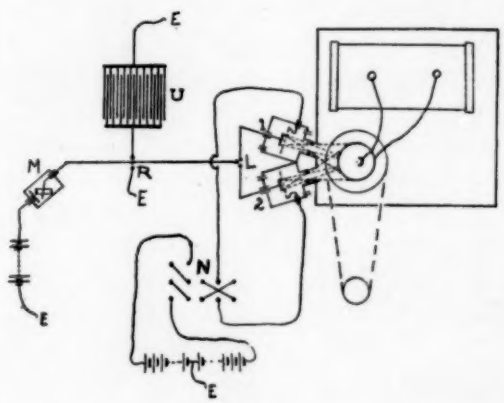

Fig. 1.

Fig. 1 represents diagrammatically the arrangement of the new apparatus.

The ionization chambers, 1 and 2, are placed so that the radiation from the X-ray bulb passes through the perforated aluminium electrodes and falls normally on the plates to be tested. As will be

shown later, the radiation from aluminium is constant, and therefore the secondary radiation from this source will not add a confusing effect. The aluminium electrodes can be charged with electricity of like or unlike sign by means of the switches N, and are kept at potentials sufficient to produce saturation. The test plates themselves formed the insulated electrodes, and the ionization currents were measured by the inclined Wilson electroscope M. The spring mercury switches L allowed either or both plates to be connected to the electroscope. The switches R connected a variable condenser U in parallel with the electroscope to reduce its sensibility, and provided a means of earthing the electroscope, condenser or plates.

The observations are made in the following manner. The electrode in chamber 1 is charged positively, and that in chamber 2, negatively. If the two plates are giving off the same amount of radiation, the electroscope will show no deflection. The plates, in spite of precautions taken, may not be equally sensitive to the primary radiation. In this case an equality of the secondary radiation may still be brought about, in general, by turning the X-ray tube about a vertical axis, until the inequality of the primary radiation falling on the two plates compensates for the difference in their sensitivenesses.

Having obtained this balance in the radiations, the "standard" plate in 1 is shielded from the X-rays. Now if any change in the sensitiveness of the trial plate takes place, when the two plates are again connected to the electroscope, a deflection will be obtained, due to the current produced by the secondary radiation from the "trial" plate being either greater or less than that from the "standard" plate.

Let us denote the original conditions by:

c_1 = current in chamber 1,
c_2 = current in chamber 2,
t_1 = time required for given deflection with 1,
t_2 = time required for given deflection with 2,
s_1 = sensitiveness of plate 1,
s_2 = sensitiveness of plate 2,

k_1 = radiation falling on plate 1,
k_2 = radiation falling on plate 2,

the units being chosen so that we may write

$$c_1 = k_1 s_1 = 1/t_1, \tag{1}$$

$$c_2 = k_2 s_2 = 1/t_2. \tag{2}$$

Now, after a certain length of time, during which the "trial" plate has been exposed, and the "standard" shielded from the X-rays, any or all of these quantities may have changed and we may denote the new values by the same letters primed.

The change in sensitiveness of the "trial" plate is given by

$$s_2' - s_2 = 1/k_2' t_2' - 1/k_2 t_2 \tag{3}$$

and the proportional change by

$$\frac{s_2' - s_2}{s_2} = \frac{k_2 t_2}{k_2' t_2'} - 1. \tag{4}$$

By preliminary test it was found that, if the test plates be of the same material, and have the same kind of surface, the balance once obtained is not disturbed by changes in the working of the coil and bulb. We may therefore assume that the distribution of the rays about the tube does not vary with the working of the coil, and we may write

$$\frac{k_1}{k_1'} = \frac{k_2}{k_2'}.$$

It was also found by trial that the sensitiveness of the "standard" plate varied but little with the intensity of the rays provided their character did not change. If the tube be kept at the same degree of hardness throughout we may then take

$$s_1 = s_1'.$$

When the radiations from the two plates are balanced, we have the condition

$$t_1 = t_2.$$

Noting these relations, equation (4) becomes

$$\frac{s_2' - s_2}{s_2} = \frac{t_1' - t_2'}{t_2'}. \tag{5}$$

But the resultant current due to the two plates working oppositely to each other is

$$c_1' - c_2' = \frac{t_2' - t_1'}{t_1' t_2'} = \frac{1}{t_d}, \tag{6}$$

where t_d is the time required for the gold leaf to move through the given deflection when both plates are connected to the electroscope at the same time.

From this it is evident that

$$\frac{s_2' - s_2}{s_2} = \frac{-t_1'}{t_d} = -\text{(fatigue)}. \tag{7}$$

We have tacitly assumed all the foregoing equations to be simultaneous, a condition impossible in practice, since readings must necessarily be taken consecutively. The error thus introduced will be that due to variations in the sensibilities, caused by changes in the character of the rays. But it will be seen from equation (7) that proportional variations in radiating power will not affect the value of the result. This requirement of proportional variation may be fulfilled by having both plates of the same metal, and their surfaces in the same condition.

An instrument sufficiently sensitive to measure t_d would be too sensitive to use for measuring t_1', since it is very small compared to t_d. To obviate this difficulty the condenser U is connected to the system when measuring t_1', thereby reducing the rate at which the potential will rise. If Q denote the total capacity of the system and condenser, and q the capacity of the system exclusive of the condenser, then we have

$$\frac{s_2' - s_2}{s_2} = -\frac{T_1' q}{t_d Q}, \tag{8}$$

where T_1' is the time required for the given deflection, when the condenser is connected and the "standard" plate alone is radiating.

The meaning of the minus sign in equations (7) and (8) is, that if the resultant deflection, after the "trial" plate has changed its sensitiveness, be in the same direction as the deflection produced by the "standard" plate alone, then the change in the "trial" plate has been a *decrease* in sensitiveness or a *positive* fatigue, and vice

versa. In practice, both t_d and T_1' were measured for deflections in the same direction and of equal magnitude, the polarity of the electrode in 1 being changed while measuring T_1' when a negative fatigue was encountered.

The variable air condenser consisted of nine stationary and eight sliding plates, each 17.6 cm. square, separated by air spaces of one centimeter each. The stationary plates were carried on sulphur pillars, and all corners carefully rounded so that leakage from even so large a surface was negligible. The condenser was free from residual charge, and all parts were nickel-plated and highly polished to prevent contact electromotive forces. For convenience, the factor q/Q was determined for various positions of the movable plates and the results plotted in a curve (Fig. 2), having for ordinates the values of q/Q, and for abscissæ the linear distance which the movable

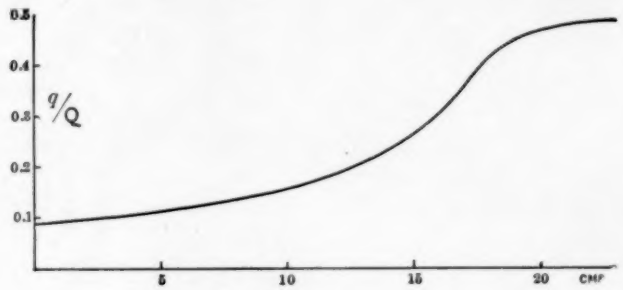

Fig. 2.

plates were withdrawn from their position of maximum capacity. In nearly all cases the condenser was used at maximum capacity, which gave the value $q/Q = 0.088$. By withdrawing the movable plates this ratio could be increased to $q/Q = 0.487$. The (calculated) maximum value of Q was approximately 350 c.g.s. units.

The results, following in this paper, have been obtained by this differential method, with the exception of a very few which have been noted.

Metals and Oxides in Air.

In Table I. are given the length of exposures and the corresponding values of the radiation from freshly polished surfaces of aluminium, copper, zinc, tin, silver, lead and iron, immersed in air. The

TABLE I.

Exposure.	Aluminium	Copper.	Zinc.	Tin.	Silver.	Lead.	Iron.
0 hrs.	100[1]	100.0	100.0	100.0	100.0	100.0	100.0
1 hr.	100	99.8	100.0	100.0	99.3	100.0	101
2 hrs.	100	100.0	99.7	99.0	99.3	—	101
3 hrs.	100	99.9	99.7	98.5	98.9	97.1	104
4 hrs.	—	—	99.4	98.1	—	—	102
5 hrs.	—	—	99.3	98.4	99.1	93.9	99
6 hrs.	—	—	—	—	98.6	94.1	—
7 hrs.	—	—	—	—	98.5	—	—

surfaces of the metals in these experiments were polished on the finest grades of crocus cloth obtainable, and were tested as soon as they became cool after polishing. The surfaces thus obtained, while not of mirror brightness in the case of the softer metals, were clean, and quite smooth and uniform.

Iron alone shows an increase in radiation, reaching a maximum in three hours. Silver, lead and tin do not show this initial rise, the silver beginning to fatigue during the first hour, and lead and tin not until the second. Aluminium and copper show no change in radiation and zinc but little.

In Tables II., III. and IV. are given the results obtained with oxidized surfaces of the same metals, the radiation from the polished metals also being given for the purpose of comparison.

The coating of magnetic oxide was prepared by heating the polished metal plate to a temperature of about 700° C., a thin even bluish black coating being thus obtained. The irregularities shown

TABLE II.

Exposure.	Freshly Polished Iron.	Magnetic Oxide.		Ferric Oxide.
0 hrs.	100	100		100
		Two samples.		
1 hr.	101	99	101	101
2 hrs.	101	101	—	101
3 hrs.	104	99	101	101
4 hrs.	102	100	100	100
5 hrs.	99	—	—	100

[1] To avoid confusion and make the nature of the results more apparent, *irregular* variations of less than 0.2 per cent. have been omitted from columns marked with the asterisk.

TABLE III.

Exposure.	Freshly Polished Copper.	Cuprous Oxide.	Cupric Oxide.	
0 hrs.	100.0	100*	100	
			Two samples.	
1 hr.	99.8	100	99	101
2 hrs.	100.0	100	99	101
3 hrs.	99.9	100	100	99
4 hrs.	100.0	—	101	101
5 hrs.	—	—	100	99
6 hrs.	—	—	100	101

TABLE IV.

Exposure.	Freshly Polished Tin.	Tin Surface Two Weeks Old.	"Tin Oxide."	Stannic Oxide.
0 hrs.	100.0	100.0	100*	100*
1 hr.	100.0	—	100	100
2 hrs.	99.0	100.0	100	100
3 hrs.	98.5	—	100	100
4 hrs.	98.1	98.2	100	100
5 hrs.	98.4	97.8	100	100

for this and the ferric oxide in Table II. are probably due to experimental errors involved in the first method, used for these determinations. The magnetic oxide may be said to show no decisive change during a four-hour exposure.

The ferric oxide coating was obtained by covering the plate with dilute hydrochloric acid, forming chloride of iron on the surface, and the ferric hydroxide, eventually produced by the addition of a few drops of ammonia, was allowed to dry. The plate was then set away for a week to allow further oxidation, after which the ammonium chloride was expelled by heating the plate. The well rusted surface thus obtained also shows no pronounced change during five hours exposure.

It will be noticed that the change in sensibility, exhibited by the polished metal, is not shown by either oxide. Both of these oxides are quite stable in air, while the metal itself is very liable to rust.

Table III. shows the behavior of the two oxides of copper.

The cuprous oxide was formed by gently heating the polished

copper plate, care being taken that the temperature did not become sufficiently high to form the cupric oxide completely. Such a coating will, at best, probably contain a considerable quantity of cupric oxide.

The cupric oxide was formed by heating the plate to dull redness in an alcohol (sulphur-free) flame. Neither of these oxides shows any fatigue in air.

These three surfaces are stable in air, and none shows variation in radiating power beyond that of experimental error.

The results of tests on two oxides of tin are given in Table IV.

The coating called "tin oxide" is of undetermined composition, but it is probably a lower oxide, or a mixture of oxides, containing less oxygen than the stannic oxide. It was formed by heating a polished tin plate to a temperature of 170° C. for several hours, and appeared as an olive to a yellowish tarnish on the surface of the metal. As might be expected from its method of formation, this surface appears to be quite stable in air at ordinary temperatures, and undergoes no further change.

The stannic oxide was prepared by igniting the nitrate formed on the surface of the metal by coating it with nitric acid.

Neither oxide shows any fatigue and the surface of the polished metal allowed to age in air for two weeks does not behave differently from the freshly polished surface.

A thin coating of a stable oxide has completely stopped the fatigue experienced by the fresh surface of the metal not thus protected.

Table V. shows the radiation from zinc, a thick and a thin layer of the oxide, ZnO.

TABLE V.

Exposure.	Freshly Polished Zinc.	Zinc Oxide, Thick Layer.	Zinc Oxide, Thin Layer.
0 hrs.	100.0	100*	100.0
1 hr.	100.0	100	100.7
2 hrs.	99.7	100	100.2
3 hrs.	99.7	100	99.5
4 hrs.	99.4	100	100.3
5 hrs.	99.3	—	100.7
6 hrs.	—	—	99.8

TABLE VI.

Freshly Polished Silver.	Tarnished Silver.
100.0	100*
99.3	100
99.3	100
98.9	100
—	100
99.1	100
—	—

The thick layer of the oxide was formed by igniting the nitrate, as with tin. The thin layer was the result of slow oxidation in air, allowed to proceed for a year and a half.

The irregularities of the figures for the thin layer are probably due to experimental error since but one of the surfaces was obtainable and a fresh surface of the metal had to be used for a "standard." As has been pointed out this may cause some error. No decisive change is shown by either surface. This oxide is quite stable in air.

The radiation from a freshly polished silver plate, and one covered with a dark tarnish, acquired by a month's exposure to the air in the laboratory, are given in Table VI. These results show a slight fatigue for the polished silver and none whatever for the tarnished surface.

Whatever may have been the nature of this tarnish, the fact of its formation indicates that it was a more stable surface, chemically, than the silver. The slight fatigue shown by the fresh metal is stopped by this protecting tarnish.

In addition an aluminium oxide surface, prepared by the ignition of the nitrate, showed no perceptible change during three hours exposure.

A coating of lead peroxide, prepared by electrolysis, did not vary appreciably during four hours exposure.

While five out of the seven metals tested, exhibit variation in radiating power, of the thirteen oxidized surfaces formed on these metals, *none shows fatigue.*

If oxidation does affect the secondary radiation, we might expect an increased effect if an oxidizing atmosphere, such as ozone, be used in place of air.

Metals and Oxides in Ozone.

The results thus far obtained for some of the metals and their oxides, when exposed in ozone, are given in Tables VII.–XIV. inclusive.

Table VII. shows the fatigue of copper, cuprous oxide and cupric oxide, and it will be observed that the fatigue decreases as the oxidation increases. The fatigue occasioned in the freshly

polished copper and cuprous oxide in two hours requires about three and one half times as long to be produced in the higher oxide.

These plates on examination after exposure showed decided changes in the character of the surface. The polished copper had become dull and had taken on the appearance of old copper surface exposed to air for some time. The cuprous oxide had changed from a reddish-brown to about the same appearance as the copper

TABLE VII.

Exposure.	Freshly Polished Copper.	Cuprous Oxide, CuO.	Cupric Oxide, CuO.
0 hrs.	100.0	100.0	100.0
⅓–½ hr.	—	—	—
1 hr.	96.3	97.0	97.8
2 hrs.	93.3	93.5	97.3
3 hrs.	91+	—	96.5
4 hrs.	—	—	95.4
5 hrs.	—	—	95.9
7 hrs.	—	—	93.4

TABLE VIII.

Freshly Polished Iron.	Magnetic Oxide, FeO.	Ferric Oxide, FeO.
100.0	100.0	100*
98.6	97.3	100
96.1	94.1	100
94.6	91+	100
94.1	90.4	100
—	—	—
—	—	—
—	—	—

had after exposure. The cupric oxide, originally black, became dark reddish-brown after seven hours in ozone.

The radiations from iron, magnetic oxide and ferric oxide surfaces are given in Table VIII., but show in this case the opposite effect with the lower oxide, that it fatigues about three times as rapidly as the freshly polished surface. Both the iron and the magnetic oxide surfaces showed that further oxidation had taken place; the polished metal had become dull and the blue-black magnetic oxide had taken on a reddish-brown cast. It is probable that the film of higher oxide, formed by the ozone on the magnetic oxide surface, was much thicker than that on the iron, which may account for the greater fatigue. The ferric oxide showed no fatigue nor was its appearance changed by the exposure.

Table IX., giving the results for tin, the "tin oxide" before described, and stannic oxide, shows again a more rapid fatigue for the lower oxide than the pure metal, and no change whatever for the stannic oxide. An inspection of the polished metal and the "tin oxide" surfaces after the test showed the formation of stannic

oxide by the ozone, the film formed on the "tin oxide" being appreciably thicker than that on the tin. The stannic oxide surface showed no change in appearance.

The fatigue of tin seems to have the peculiarity of being slow in starting under any conditions, not appearing until the third hour in ozone, while the other metals experience from one to four per cent. fatigue during the first hour of exposure in this gas.

The fatigue for the fresh surface of zinc, and for a surface cov-

TABLE IX.

Exposure.	Freshly Polished Tin.	"Tin Oxide."	Stannic Oxide, SnO.
0 hrs.	100.0	100.0	100*
½ hr.	—	99.1	—
1 hr.	100.0	—	—
2 hrs.	100.0	97.9	100
3 hrs.	98.4	97.3	100
4 hrs.	99.2	95.6	100
5 hrs.	96.8	94.2	—
6 hrs.	94.1	—	—

TABLE X.

Freshly Polished Zinc.	Zinc Oxide, ZnO.
100.0	100*
98.2	—
96.6	100
95.2	100
—	100
—	—
—	—
—	—

ered with a layer of zinc oxide, when exposed in ozone, are given in Table X.

The radiation from the freshly polished surface diminishes rapidly, while that from the zinc oxide surface remains constant.

The results with a freshly polished surface of silver, and a surface coated with silver oxide, are given in Table XI.

Table XII. shows the behavior of aluminium and aluminium oxide surfaces, exposed in ozone.

The silver and aluminium surfaces fatigue, while their oxides show no appreciable variation.

The radiations from lead and lead peroxide are given in Table XIII.

The lead peroxide fatigues at about the same rate as the freshly polished surface during the first hour, and then remains nearly constant. This coating of lead peroxide was porous and undoubtedly allowed the ozone to penetrate to the metal itself, where perhaps some slight further oxidation took place.

All the metallic surfaces after exposure showed evidence of oxidation, the lead especially being badly tarnished.

By comparison of Tables IX., XI. and XIII. with Table I. it will be seen that the fatigue of tin, silver and lead progresses at about twice the rate in ozone that it does in air. Comparison of Tables

TABLE XI.

Exposure.	Freshly Polished Silver.	Silver Oxide, AgO.
0 hrs.	100.0	100*
½ hr.	98.8	—
1 hr.	97.7	100
2 hrs.	97.5	100
3 hrs.	98.1	100
4 hrs.	97.5	—
5 hrs.	97.0	—
6 hrs.	96.9	—

TABLE XII.

Exposure.	Freshly Polished Aluminium.	Aluminium Oxide, AlO.
0 hrs.	100.0	100*
⅓ hr.	97.8	100
1 hr.	95.7	100
2 hrs.	95.7	100

X. and I. shows that zinc fatigues about fifteen times as fast in ozone as in air.

Platinum and palladium plates were exposed in ozone, and as will be seen from Table XIV., their radiations remain constant

TABLE XIII.

Exposure.	Freshly Polished Lead.	Lead Peroxide, PbO.
0 hrs.	100.0	100.0
⅓ hr.	98.6	—
1 hr.	97.7	97.1
2 hrs.	95.1	97.3
3 hrs.	93 ±	97.0

TABLE XIV.

Exposure.	Platinum.	Palladium.
0 hrs.	100*	100*
1 hr.	100	100
2 hrs.	100	100
3 hrs.	100	100

within the limits of experimental error. These two metals are unaffected by ozone.

Lastly, a few experiments were tried to determine the radiating powers of these oxidized surfaces compared to the polished metals, and the results for copper and iron and their oxides are given below.

Cu	100	Fe	100
Cu_2O	95	Fe_3O_4	94
CuO	92	Fe_2O_3	84

The cuprous oxide and ferro-ferric oxide films were very thin, perhaps not over a few wave-lengths of light in thickness, and yet

their effect on the secondary radiation is very marked. The same qualitative relations hold for the tin oxide surfaces, and in fact it may be said, that in every case in our experience the radiation decreases as oxidation progresses.

During the course of the experiments a tin and a silver plate accidentally became amalgamated, and I was surprised to note that these mercury-coated surfaces gave much more radiation than the pure metals. Quantitative measurements of this increase in sensitiveness have not yet been made.

The seven (oxidizable) metals, and three lower oxides tested, *all* showed fatigue when exposed in ozone. Of the seven highest oxides, but two showed *any* fatigue and that relatively small. The sensitiveness of the two metals unaffected by oxygen, platinum and palladium, remains constant.

The fatigue suffered by the cupric oxide was probably due to the further oxidation of sub-layers of the lower oxide which we might expect to be present. The change in appearance of the surface indicates some chemical reaction or physical change, which might produce a variation in the radiating power.

The behavior of the lead peroxide may possibly be explained on a similar basis.

Summary.

Freshly polished surfaces of lead, tin, silver and iron show fatigue in air, while those of aluminium, copper and zinc experience little or no change in their secondary radiation.

None of the oxidized surfaces shows any fatigue in air.

All the metals tried, except platinum and palladium, gave fatigue in ozone, with accompanying change in appearance due to oxidation.

All the lower oxides tested fatigue in ozone.

None of the highest oxides, with the exception of cupric oxide and lead peroxide, shows any change in sensitiveness.

Metals not subject to oxidation do not fatigue in ozone.

The radiating power of surfaces decreases as oxidation progresses.

The results obtained by Professor More have been confirmed with the exception of those for unpolished zinc and freshly polished lead in air, although in either case it would be difficult to say whether

or nor the surfaces of the plates were in the same condition in the two experiments.

CONCLUSION.

It appears from these results that there is a close relation between the behavior of the surface when exposed to X-rays and its "chemical stability."

The theory that fatigue is due to great absorptive power of ozone, when absorbed or adsorbed by the metal, is evidently not applicable to this case, since it does not account for the absence of fatigue from a chemically stable surface.

The results are also against disintegration theories, for particularly in the ozone experiments there were just as many atoms to disintegrate after oxidation as before, in fact a number of oxygen atoms have been added. If a density law of absorption holds, the oxides would probably have less absorbing power than the metal itself, and the decrease in radiation cannot be accounted for by assuming increased absorption of the radiation coming from the body of the metal. This limits the secondary radiation mainly to a surface effect.

The explanation of fatigue upon a basis of chemical change would lead us to expect that the more stable a surface the less the fatigue. This order is followed, without exception, in the results given.

In conclusion, I wish to extend to Professor More my most sincere thanks and appreciation, for his suggestions and direction of this work. Thanks are also due to a grant from the Bache Fund of the National Academy of Sciences which greatly facilitated the work.

UNIVERSITY OF CINCINNATI,
May, 1909.

THE ROTATORY POWER OF LIMONENE AT LOW TEMPERATURES.[1]

By F. A. Molby.

THE work described in this paper is a continuation of the study of the effect of low temperatures upon the optically active substances, the first results having been published in the January number of the Physical Review of the present year. The former paper contained a description of the apparatus used in the study of quartz. The apparatus used in the study of limonene is essentially the same, namely, a Lippich triple field polariscope of most recent and improved construction (Schmidt & Haensch), graduated in circular degrees and hundredths of a degree, and an iron-constantan thermo-couple, with potentiometer, for measuring temperatures. The range of temperature through which the limonene has been studied is from 20° to — 130°. For the most part the observations end at — 120°.

The limonene studied was procured through the Fritzsche Brothers of New York. It was ordered especially for this work and bears Schimmel and Company's (of Leipsig, Germany) mark "limonene pure." Occasion is here taken to thank the firm for furnishing the special order free of charge. The sample was secured from the manufacturers in July, 1908, and the package was kept unopened until March of this year. It is hoped that by keeping it thus and by using much care to prevent contamination and to prevent oxidation by exposure to the air, the results will be faultless so far as the purity of the specimen can enter into them.

As considerable difficulty was encountered in obtaining a satisfactory tube for observations, due to the very great solvent power of the liquid on all rubber washers or organic seals tried for making joints, the tube used will be described here with a view of a

[1] The substance of this paper was in part given at the April meeting of the Physical Society in Washington.

vertical section through the tube and cooling device. The illustration is drawn accurately to scale.

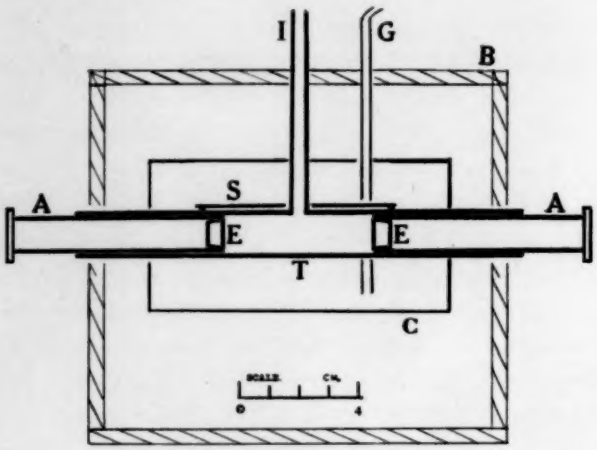

Fig. 1.

T is a glass tube 15 cm. long and 1.4 cm. inside diameter. *AA* are two glass air cells 8 cm. long and 1.1 cm. inside diameter. *E E* are of plate glass 8 mm. thick and ground into *AA*, intended for making vacuum cells. *I* is an intake tube through which the thermo-junction is inserted. *C* is a tin can for cold air space around *T*. *S* is a sheet copper saddle leaving 2 mm. air space around *T*. *G* is a glass tube extending into the bottom of the can *C*.

As the limonene soon dissolved out any tallow or wax seal on *EE* and passed through as a vapor, the idea of exhausting the air from the tubes *AA* had to be abandoned. Black paper tubes were fitted inside *AA* with a thin space between them and the glass for phosphorus pentoxide. The outside diameter of the air cells is just small enough to allow them to be slipped inside of *T* so that the joints between *T* and *AA* are 5 cm. from the cooled liquid, and a seal of water glass forms insoluble joints which are not exposed to extreme cooling. The length of tube left between *AA* for the specimen to be observed is 4.97 cm. The wooden box *B* serves as a holder for the tube and for a form into which wool is packed for insulating the tube from the exterior. The inside wall of the box is lined with bright tin to help insulate the tube and cooler.

The glass tube G is, during a set of readings, connected to a Dewar flask of liquid air and the cooling of the specimen is accomplished by blowing liquid air over in small quantities. The key of the potentiometer is kept closed with one junction of the thermo-couple in the limonene while the other is in cracked ice (but protected by a thin glass tube), so that small changes of temperature are at once apparent and by careful watching the temperature of the specimen can be held at any temperature with not more than one half of one degree variation from the mean temperature desired. The copper saddle is for the purpose of securing uniform temperature along the specimen, which is very much aided by the fact that the liquid air evaporates at once on reaching the bottom of the tube G and causes a good circulation of the air surrounding the tube T. The thermo-couple responds so quickly to changes made by the cold air supplied that there is apparently a good thermal conductivity in the limonene and the results also tend to show that the temperature distribution is good.

The calibration of the thermo-couple is somewhat different from that in the work with quartz. The usual second degree equation did not give a curve passing through all of the observed points, so a third degree equation of the form

$$E = at + bt^2 + ct^3$$

was assumed, and the constants were found from the values observed between ice and steam, between ice and CO_2 ether paste, and between ice and liquid air (by analysis of air). From these constants intermediate E.M.F.'s were computed and a smooth curve drawn through the plotted points. The table follows as used.

TABLE I.

T	−192°	−182°	−160°	−140°	−130°	−120°	−100°
$E \times 10^{-5}$	−810	−782	−714	−644	−606	−567	−484
T	− 78.3	− 60	− 40	− 20	0	30	99.2
$E \times 10^{-5}$	−388	−302	−205	−104	0	160	538

Observations have been made with several wave-lengths of light. With any one wave-length the observations extended over four or

five hours. For the most part ten settings of the polariscope were made for any one temperature of the limonene while the temperature was held practically constant for fifteen or twenty minutes. The temperature was then lowered as many degrees as desired and a number of settings made for the new temperature; the process was then repeated at 15 to 20 degree intervals until a series for the one wave-length was completed. In further work some method might be used by which observations can be made on the several wave-lengths one after the other at a single cooling of the substance. The wave-length 589.2 $\mu\mu$ was obtained by using a sodium light from a double Bunsen burner with a solution of potassium bichromate in the small cell at the front of the polarization apparatus. The wave-length 670.8 $\mu\mu$ was obtained by holding an asbestos sponge in the lower part of the Bunsen flame, the sponge being saturated with lithium chloride; the bichromate solution was removed from the cell in front of the polarizer and two thicknesses of color screens were put in place of the cell, the screens having been first tested with a direct vision spectroscope to see that only the red light of the lithium was transmitted. The wave-length 435.9 $\mu\mu$ was obtained by means of a spectroscope in connection with a Cooper-Hewitt mercury arc lamp; the slit of the instrument was opened quite wide and the images of the slit were formed on a black paper screen with a slit only wide enough to transmit one image at a time. The polarizer was placed about 20 cm. from the slit so that the light diverging from the image illuminated the field of the polariscope satisfactorily. A methyl violet screen was placed between the polariscope and the image to absorb stray light that otherwise came from the other colors of the arc spectrum. The wave-length 546.1 $\mu\mu$ was obtained in the same way as the wave-length 435.9 except that the slit of the telescope was made much narrower and the distance from the image of the slit to the polarizer was somewhat greater. The wave-length 491.6 was too dim to be of any use as obtained in the above manner from the mercury arc. A combination of two screens, an alkali blue screen and a yellow colored one found in a collection of colored screens, was found to absorb completely all wave-lengths of the mercury arc spectrum except 491.6 $\mu\mu$. A condenser system similar to that used on an arc

lantern was placed between the mercury arc and the polarizer to make stronger illumination of the polariscope field, while the screens formed a window through a box used for shielding the apparatus and observer from the light of the arc. The several wave-lengths used were carefully identified by a calibrated spectrophotometer, and the purity of the light was in each case tried by the direct vision spectroscope.

Throughout the work the same waterglass joints have been in use so that the tube length is the same for all. The polarization angle of the polarizer, *i. e.*, the angle between the principal plane of the large polarizer and the principal plane of the small polarizers, has been the same.

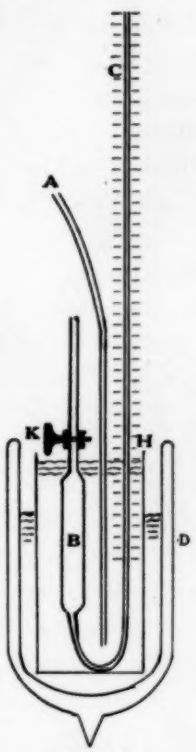

Fig. 2.

In dealing with the temperature effect upon the optical activity of a liquid substance, the change in density of the liquid will increase the number of active molecules in a given linear distance if the liquid becomes more dense or decrease the number if the liquid becomes less dense. As the change in density of the limonene with temperature is such as to produce in part the increased optical activity of the substance observed upon cooling the limonene, the following approximately correct density determinations were made through the range of temperatures used.

The absolute density of the limonene at 20° was found by weighing a 25 c.c. specific gravity flask on a chemical balance. The net weight of distilled water in the flask was 24.917 grams weight in air. The net weight of the limonene in the flask was 21.222 grams weight. The ratio of the two weights gives the relative density of the two materials, which multiplied by the density of the distilled water at 20° gives the absolute density of the limonene to be .850 at 20° C. In order to find the density of the limonene at other temperatures the expansion of a given volume was observed between —115° C. and 30° C. while it warmed up through about four hours of time. The apparatus used for the purpose is shown in ver-

tical section in Fig. 2. A stop-cock K was sealed into a glass bulb B and to the other end of the bulb was sealed a long tube of small cross-section. This tube C was bent as shown in the figure so that the lower part of the U-shaped portion was 48 cm. from the open end of the tube C. The cross-section of the tube C was .085 sq. cm. With the tube B inverted the limonene was forced through the stop-cock into the bulb B. The bulb B was then inserted in the tin can H and the can H was filled with petroleum ether, thus surrounding the bulb up to about 2 cm. of the stop-cock. The can H was placed in a Dewar cylinder D and surrounded with petroleum ether and liquid air. A millimeter scale was attached to the long tube C so that the height of the liquid could be read at any temperature. On cooling the limonene the stop-cock was opened and the tube C filled to a point opposite the letter B in the figure. The petroleum ether was continually stirred by a stream of air forced to the bottom of the can H through the tube A leading from a tank of compressed air. The top of the whole was covered by loose wool. The temperature of the bath was measured by the

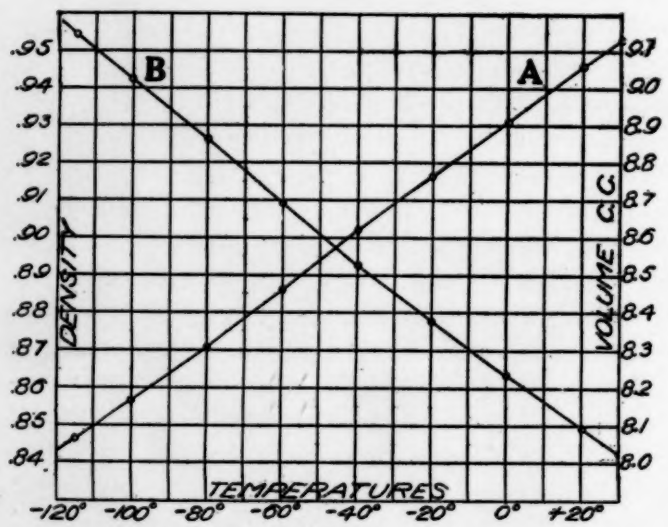

Fig. 3.

thermo-junction inserted in the petroleum ether. Frequent excursions made through the bath with the junction showed the tempera-

ture to be fairly uniform. The volume of the tube B and the stem C was calibrated later with mercury measured out from pipettes of 5 c.c. capacity and small cross-section so that volumes could be read with reasonable accuracy to .01 c.c.

Curve A in Fig. 3 shows the volume of limonene in the apparatus at the various temperatures. The apparent change of volume is somewhat less. A simple calculation using three times the linear coefficient of expansion of glass[1] as volume coefficient gives the volume of glass at $-120°$ to be less than at 30° by the amount $3 \times .000008 \times 150 \times 8$ c.c. or .0288 c.c., while the apparent changes as measured in the tube C could be read accurately to $.02 \times .089$ c.c. or about .0018 c.c. The change of volume for the same range of temperature was from the curve A equal to 1.1 c.c. so that we have the relative expansion of the limonene about forty times larger than that of glass. If we assume the curve A to be a straight line the mean coefficient of expansion of the limonene between 30° and $-120°$ is

$$B = \frac{9.13 - 8.03}{9.06 \times 150} = .00081,$$

9.06 being the volume at 20° C.

In my experiments I have found the liquid to solidify at $-130°$ to $-135°$ C. Its boiling point is 175 or 176 as given by various authorities. It is seen to have a coefficient of expansion several times larger than that of mercury and it is suggested that the substance possesses some if not all of the properties needed to make thermometers with a range of two hundred and eighty or possibly three hundred degrees.

Fig. 3, curve B, shows the density of the liquid over the range of temperature used. The density at any temperature t was found by the formula

$$D_t = \frac{D_{20°} V_{20°}}{V_t}.$$

D_{20} represents the density at twenty degrees and V_{20} represents the volume at twenty degrees and V_t represents the corrected volume

[1] H. G. Dorsey, PHYS. REV., Vol. 25, p. 98.

of the limonene at any temperature t as read from the curve A, Fig. 3.

TABLE II.

Limonene.

Wave-length 435.9 μμ.			Wave-length 491.6 μμ.		
Temp.	Obs. R.	$[a]_t$	Temp.	Obs. R.	$[a]_t$
22°.2	98°.0	232°.5	22°.0	73°.6	174°.6
− 0.4	103.5	241.0	− 12.2	79.9	184.3
− 22.5	109.0	249.3	− 30.4	83.1	188.4
− 47.0	115.7	259.3	− 51.0	87.1	194.5
− 66.0	120.9	266.2	− 74.5	92.0	201.1
− 80.6	126.2	274.3	− 85.0	94.3	204.1
− 92.0	129.1	277.8	−104.0	98.9	210.7
−102.0	132.5	282.7	−120.8	102.2	214.6
−115.0	137.1	289.3			
−123.0	139.7	292.9			
Wave-length 546.1 μμ.			**Wave-length 589.2 μμ.**		
Temp.	Obs. R.	$[a]_t$	Temp.	Obs. R.	$[a]_t$
20°.5	57°.2	135°.7	22°.2	48°.8	115°.9
− 0.5	60.2	140.2	.0	51.5	120.0
− 20.5	63.0	144.5	− 18.0	54.0	124.0
− 40.8	66.0	148.8	− 64.0	59.9	132.1
− 54.0	68.3	152.1	− 76.4	61.9	135.0
− 67.0	70.5	155.0	− 89.0	63.8	137.7
− 79.7	73.1	159.0	−103.7	66.4	141.4
− 89.7	75.3	163.0	−114.0	67.8	143.2
−116.4	81.6	172.0	−118.0	68.3	143.8
−124.5	84.2	176.0	−123.0	69.3	145.4
			−125.7	69.9	146.4
			−128.0	70.0	146.3
Wave-length 670.8 μμ.			**Wave-length 670.8 μμ.**		
Temp.	Obs. R.	$[a]_t$	Temp.	Obs. R.	$[a]_t$
21°.0	35°.9	85°.1	− 82°.0	46°.3	100°.4
4.0	37.3	87.1	−102.0	49.4	105.6
− 9.0	38.6	89.2	−108.0	50.2	106.5
− 24.2	39.9	91.2	−120.7	52.1	109.4
− 41.0	41.5	93.6	−123.5	52.2	109.5
− 61.0	43.6	96.5			

The specific rotation of a pure liquid active substance is defined by the equation

$$[a]_t = \frac{(a)_t}{L_t D_t},$$

where $[a]_t$ is the specific rotation, $(a)_t$ is the observed angle of rotation of the plane of polarization, D_t is the density of the liquid at the temperature t and L_t is the length of the column of liquid at the temperature t in decimeters of length.

Table II. gives the observed rotations for the various wave-lengths at the various temperatures, temperature being read from the curve of E.M.F.'s described in connection with Table I. The third column under each wave-length gives the specific rotation of the liquid as computed by use of the formula above. The density of the liquid for use in the formula was read from the curve B in Fig. 3.

The curves in Figs. 4, 5, 6, 7 and 8 are plotted from the values

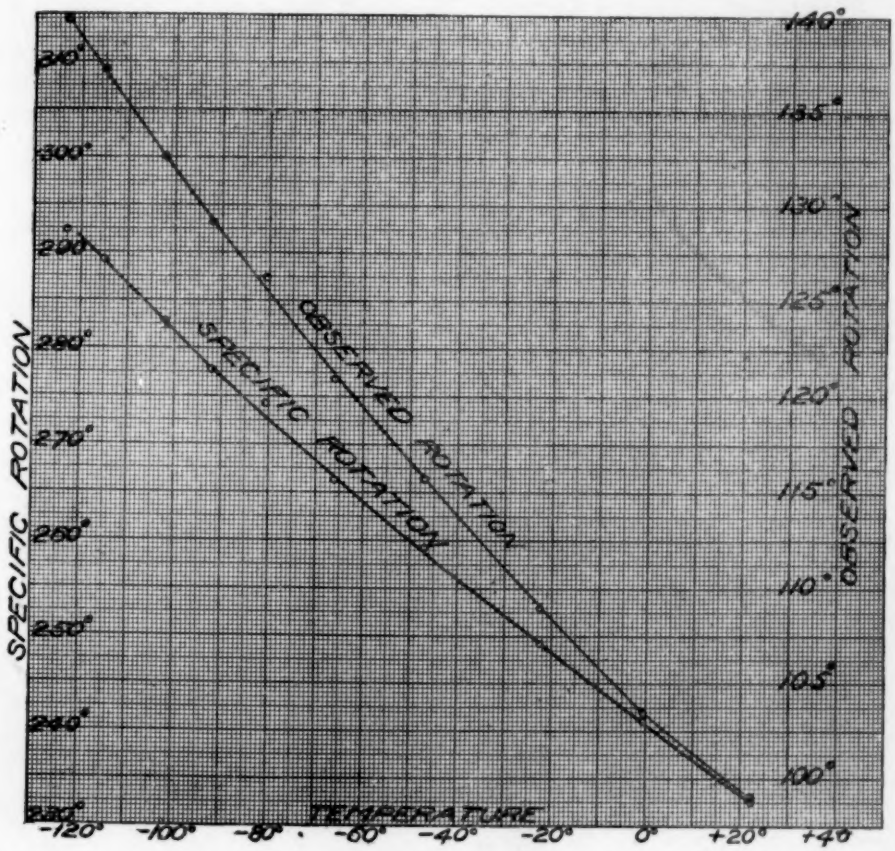

Fig. 4. Wave-length 435.9 $\mu\mu$.

given in Table II. The upper curve in each of the five figures shows the observed rotation for a column of the liquid whose length was 4.97 cm. at 20°, and which changed but little on cooling as the tube was made of glass. The rotations corresponding to the upper curve in each of the five figures are given on the right-hand margin. The rotations corresponding to the lower curve in each figure are given on the left-hand margin. The abscissæ are the temperatures

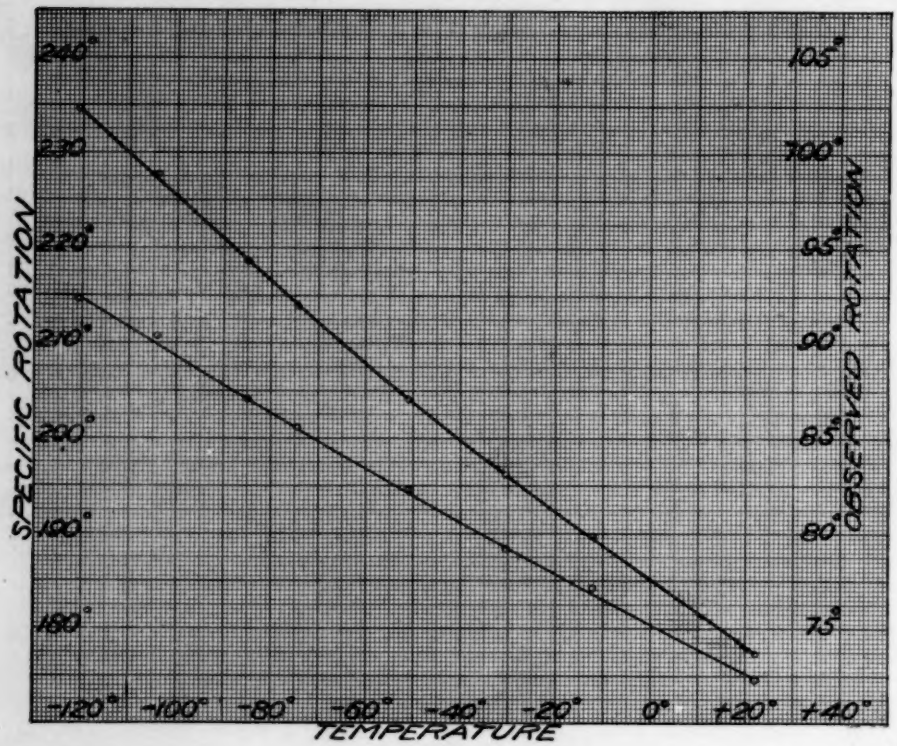

Fig. 5. Wave-length 491.6 $\mu\mu$.

at which observations were made. The two curves are thus given in order to show what part of the observed change in optical activity may be explained by the presence of an increased number of active molecules in a given linear distance, and what part of the increased rotation is due to the increased activity of the individual molecules when they are subjected to a loss of temperature which means, of

course, a loss of molecular energy so far as molecular vibration due to temperature is concerned. The Fresnel explanation of optical rotation, which looks upon the active substance as being capable

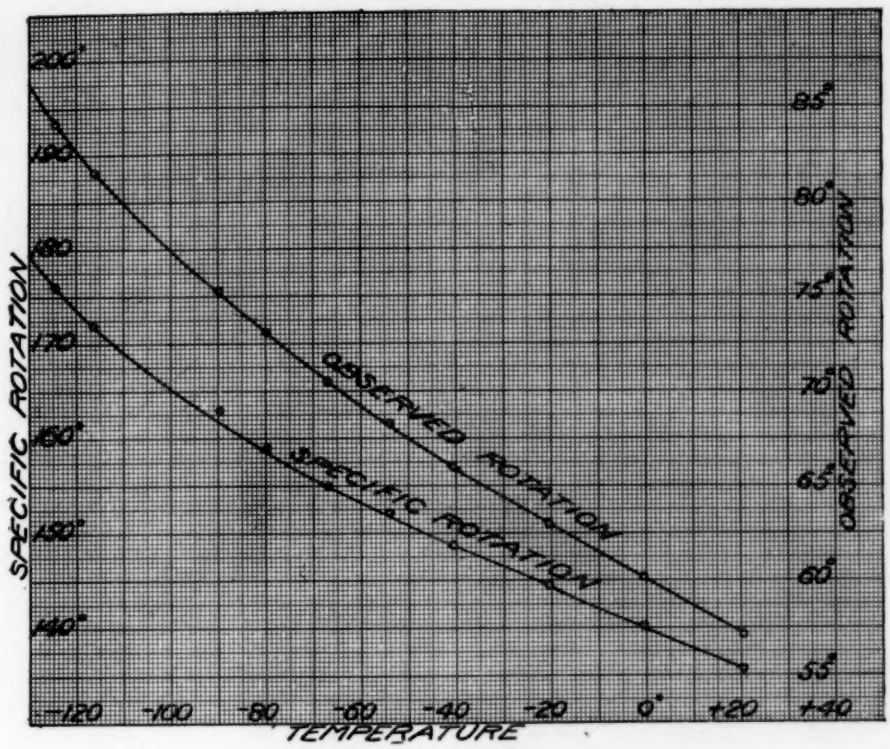

Fig. 6. Wave-length 546.1 $\mu\mu$.

of splitting a beam of plane polarized light into two circularly polarized beams having oppositely directed vibrations which unite to form a plane polarized beam again upon their emergence from the active substance but polarized in a different plane because of the different velocities with which the two beams travel through the substance, is made to explain the phenomena dealt with in this paper by simply saying that the refractive index of the substance, being different at room temperature, for the two circularly polarized beams, is rendered still more different by diminishing the temperature of the substance. Reference to the curve shows that

no one of the specific rotation curves for any of the wave-lengths is strictly or even approximately a straight line function of the temperature. Based upon this fact, and also referring to the curve published in the January number of the PHYSICAL REVIEW showing that for quartz the rotation temperature curve is not a straight line, the following conclusion is offered. [It should be noted that for quartz the rotation is diminished, not increased, by cooling, but

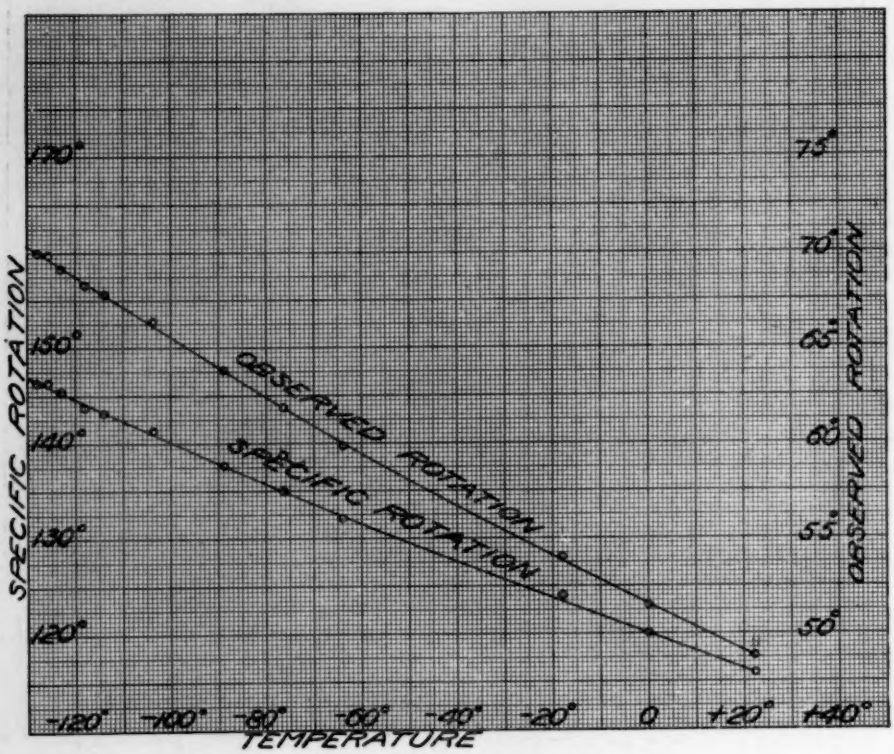

Fig. 7. Wave-length 589.2 $\mu\mu$.

that the flexure of the curve in question is in the same direction as that for the limonene curves.]

The indices of the substance for the two circularly polarized beams do not continue to bear the same ratio to each other on cooling the substance. For the amount of rotation produced is proportional to the

length of the linear path through the substance. From this it appears that the amount of rotation is proportional to the difference of

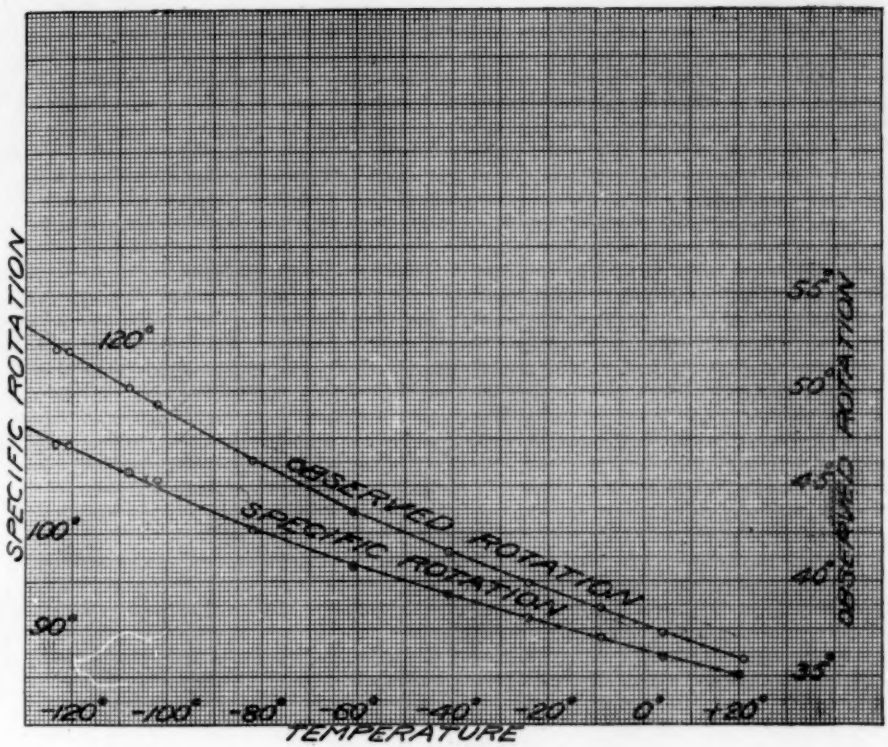

Fig. 8. Wave-length 670.8 $\mu\mu$.

phase brought about between the two beams during their passage through the substance. But the phase difference brought about is also proportional to the difference between the indices of refraction for the respective beams. Hence if the index for the one circularly polarized beam bore a constant ratio to the index for the other circularly polarized beam we would obtain a straight line when plotting temperatures and specific rotation for the substance. On the other hand, *the indices of refraction of the substance for the two circularly polarized beams are not increased by the same absolute quantity on cooling the substance*, for if they were the curve between temperatures and specific rotation for a given wave-length would be

a straight line parallel to the axis of temperature, *i. e.*, a change in temperature would produce no change in the specific rotation of the substance.

The five curves in Fig. 9 show the *rotary dispersion* of the limonene at $-120°$, $-90°$, $-60°$, $-20°$ and $20°$ respectively, beginning with the upper curve in the figure. The points on the curves in Fig. 9 were read off from the specific rotation curves in Figs. 4, 5, 6, 7 and 8. In form the curves resemble those obtained

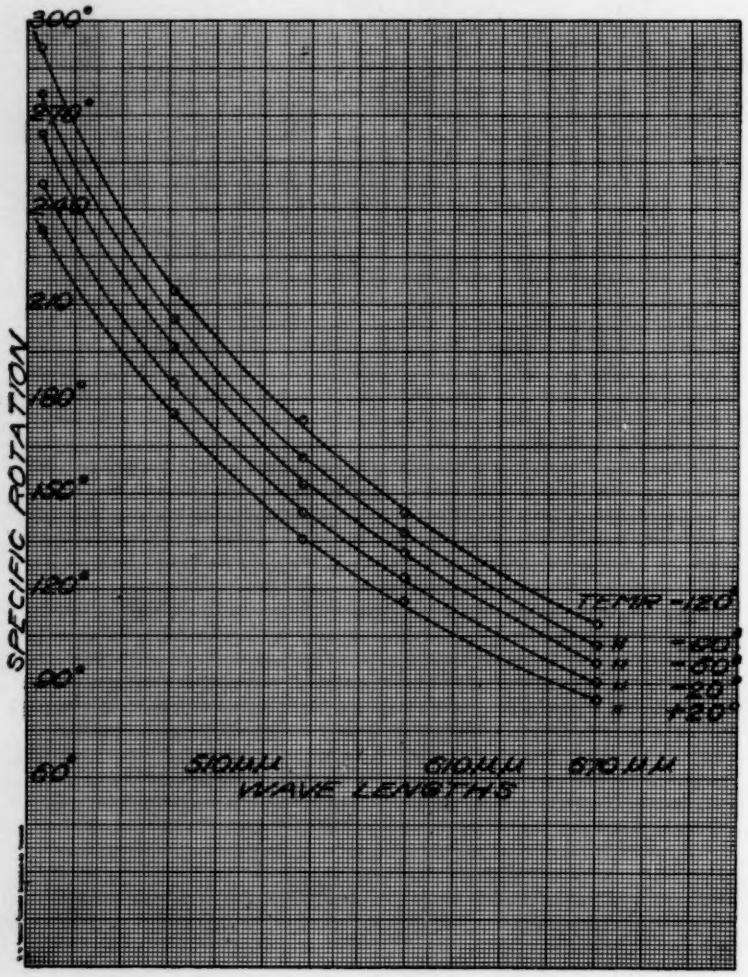

Fig. 9. Rotary dispersion.

by Mr. P. G. Nutting[1] for several of the substances used by him in his work on ultra-violet rotary dispersion. In comparing them, however, they should be compared only in that part of the spectrum covered in my work. On page 8 of his article is given a curve of rotary dispersion of limonene which he stated was not of the form that should be expected and which is quite dissimilar to the curves here published.

The work will be continued with other of the substances which admit of low temperature study.

CORNELL UNIVERSITY, June, 1909.

[1] PHYS. REV., Vol. 18, July, 1903.

THE ABSORPTION OF LIMONENE AT LOW TEMPERATURES.

BY F. A. MOLBY AND R. C. GIBBS.

IN the previous article Mr. Molby has recorded the effect of low temperatures on the rotatory power of limonene. In obtaining the measurements here described he and Mr. Gibbs used the apparatus previously set up and calibrated by the latter for use in his spectrophotometric studies.[1]

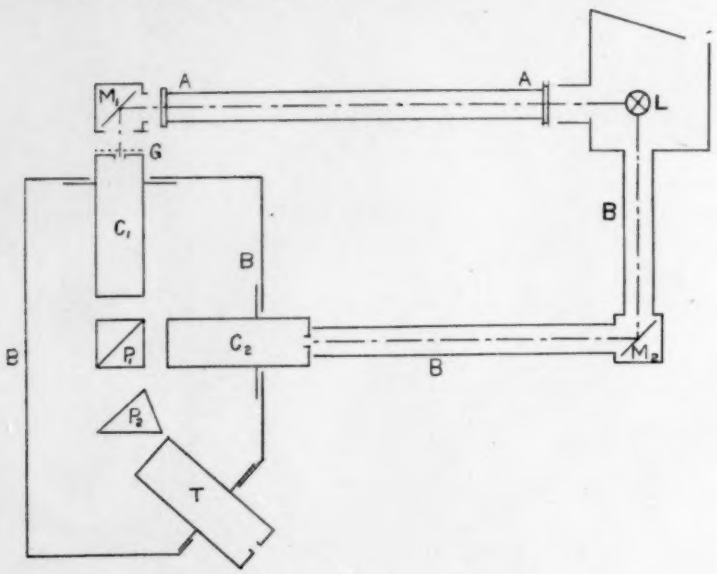

Fig. 1.

Fig. 1 shows the arrangement of the apparatus. The tube containing the limonene is represented by *AA* (the detailed construction and method of mounting this tube are shown in the previous article). Light from an enclosed acetylene flame *L* passed through this tube and was reflected by a glass mirror M_1 through the slit of one of the collimators of a Lummer-Brodhun spectrophotometer shown in Fig.

[1] PHYS. REV., Vol. XXVIII., May, 1909.

1. A piece of ground glass G was securely fastened to the front of this collimator in order to secure a uniform field. Light from the same flame was reflected by a block of magnesium carbonate M_2 through the slit of the other collimator, thus precluding the discrepancies of separate transmission and comparison sources.

A series of readings throughout the spectrum was made with the empty tube in place; the limonene was then poured into the tube and six sets of measurements were made through the spectrum, the first with the temperature of the limonene at 22°, then at — 4°, —30°, — 60°, — 90°, and at — 125° C. Each observer made independent readings for every point measured and the mean of the two observations was used. The curves in Fig. 2 show the ratio of transmitted

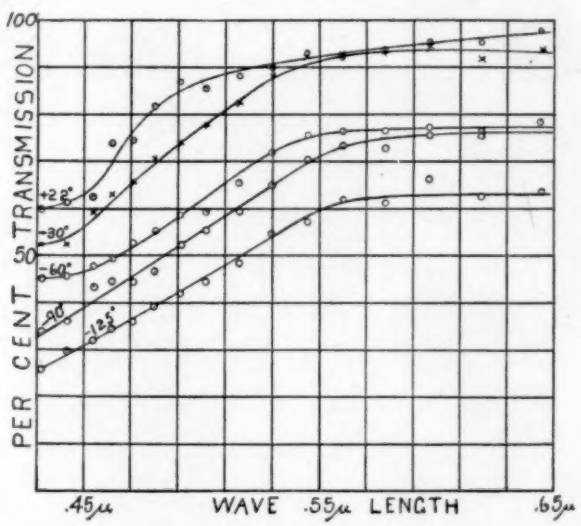

Fig. 2. Showing the percentage transmission at the various temperatures.

light to incident light for all the above-mentioned temperatures except — 4°, which curve, if plotted, would lie between the curves for 22° and — 30°. It has been, therefore, omitted to avoid confusion with these curves. The curves in Fig. 3 show the coefficients of absorption of limonene for the various parts of the spectrum at the extreme temperatures used. These coefficients were obtained from

the data of the corresponding curves in Fig. 2, by the use of the equation

$$\beta = \frac{\log I - \log T}{x},$$

where β is the coefficient of absorption, I the intensity of incident light, T the intensity of transmitted light, and x the thickness in centimeters of the limonene traversed by the light.

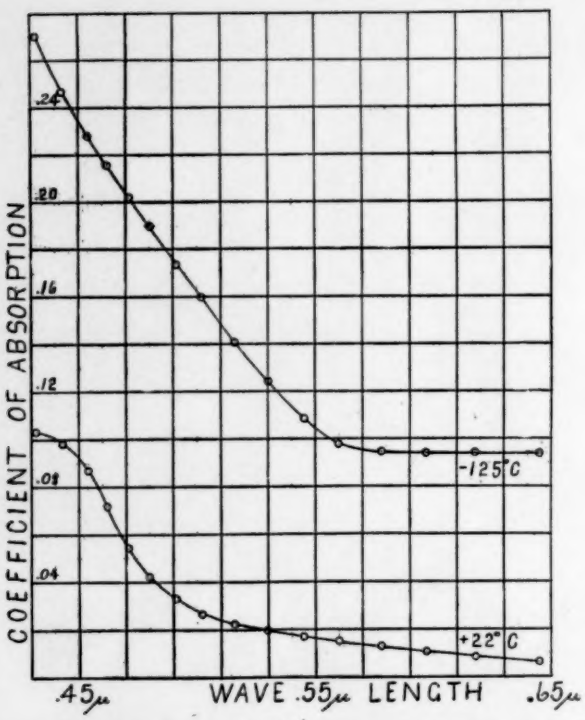

Fig. 3. Showing coefficient of absorption, β, for 22° and — 125° C.

The curves in Fig. 2 show a considerable increase in the absorption of limonene as the temperature is decreased and that the rate of increase per degree is much larger at the lower temperatures. These curves as also those in Fig. 3 show that the absorption band is considerably broadened in the direction of the longer wave-lengths when the temperature is reduced to — 125° C.

It should be mentioned that all surfaces on which the collection of frost or moisture would result in incorrect readings for the transmitted light, were carefully watched and neither frost or moisture was detected when the above-described measurements were made.

In view of the more or less general law that absorption decreases on lowering the temperature, it seemed advisable to measure the light transmitted through the empty tube at temperatures below that of the room, in order to determine whether the decrease in transmission was to be accounted for in whole or in part by some change in the tube itself. After proper precautions had been taken to eliminate the collection of frost or moisture on the inside surface of the ends of the tube, no material change in the transmission through the empty tube was observed throughout the entire range of temperature above mentioned.

PHYSICAL LABORATORY,
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POLARIZATION OF RÖNTGEN RAYS.

BY WM. R. HAM.

THE ether pulse theory of Röntgen rays would lead us to expect a greater intensity of the rays in a direction at right angles to the kathode stream than in the direction of that stream. All efforts which have thus far been made to detect any such difference by direct observation on the primary rays have given negative results. The latest attempt was made by Haga.[1]

Barkla, however, has concluded from observations on secondary X-rays, that the primary rays are partially polarized, and has investigated qualitatively the effect upon this polarization of variation in the hardness of the tube used. His results have been verified by Haga.[2]

At the Christmas meeting of the American Physical Society in 1907 at Chicago, the author showed that the intensity around certain X-ray tubes varied in such a manner as to indicate some polarization, the intensity being measured in these experiments by the rate of discharge of electroscopes.

Since that time the work on the polarization of X-rays has been carried on continuously with apparatus modified from time to time as sources of error became apparent.

The aim of the investigation has been to answer the following questions:

1. Can a polarization be shown to exist by direct observation on the primary beam itself?

2. If so, is the intensity a maximum in the plane normal to the kathode ray stream?

3. Does the intensity diminish symmetrically on either side of this plane?

[1] H. Haga, Ann. d. Physik, 23, 3, pp. 439–444, 1907. Since this paper was written my attention has been called to some very recent work by Herwig (Ann. d. Physik, 29, 7, pp. 398–400, 1909) upon a carbon target, which perhaps constitutes an exception to the above statement.

[2] C. G. Barkla, Phil. Trans., A., 204, p. 467.

4. What effects do changes of potential and of gas pressure have upon the polarization?

5. What effects do absorbing sheets of different materials have upon the polarization?

These questions will be discussed in Part I.

In the course of the investigations it has also been found possible to make accurate determinations of:

6. The coefficients of absorption of certain materials for rays of a given hardness.

7. The variation of these coefficients with the hardness of the tube.

8. The mean depth in the target at which the rays originate.

9. The variation of this mean depth with hardness.

The last four points will be discussed in Part II.

Arrangement of Apparatus.

The method employed for measuring and controlling potentials was one which was being used in the laboratory by Professor Millikan and which he had found to yield satisfactory results.

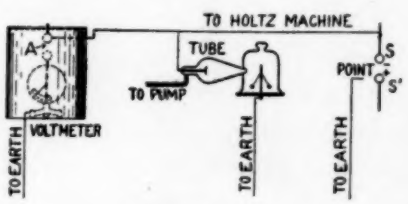


Fig. 1.

In Fig. 1, SS' are terminals of a twelve-plate Holtz machine, motor driven. Near the positive terminal is a single point connected to earth. The negative terminal is connected directly to the tube and to A.

A is an air condenser in series with a Braun voltmeter. The voltmeter reads direct to 10,000 volts. With the air condenser in series, the reading must be multiplied by a constant varying from 6.0 to 6.4 according to the length of the gap which was used. This combination was calibrated by a transformer having a secondary of twelve divisions, a Kelvin E.S. voltmeter being connected across one of these divisions. The calibration was repeated with an absolute electrometer of large size. The arrangement was found quite satisfactory, the readings of the potential between limits of 9,000 and 30,000 volts being probably correct to 2 per cent., and rela-

tively correct to 1 per cent. The tube is placed between the static machine and the voltmeter, its distance from either being about 2 meters.

CONSTRUCTION OF TUBES.

The two types of tubes principally used are illustrated in the diagrams of Fig. 2 (*a*, *b* and *c*).

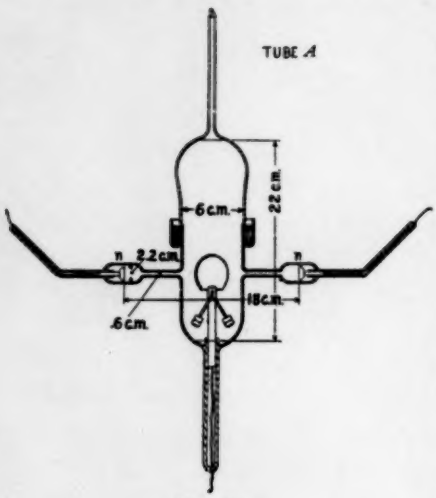


Fig. 2*a*.

The following points are to be noted:

1. It is necessary that the rays emerging from the tube in different directions pass through glass walls of exactly the same thickness. On measuring the thickness of the glass in different parts of the common commercial Röntgen ray tubes, wide variations were found, so wide in fact as to make untrustworthy any comparison of intensities in various directions. It was also found impossible to correct for the absorption of the glass in such tubes.

Two types of tubes, illustrated by *A* and *B*, were used to eliminate this source of error. *A* is a tube constructed from a selected glass cylinder of very uniform thickness; *B*, a tube with windows *a*, *b*, *c*, *d*, *e*, cut from a given selected sheet of glass of uniform thickness.

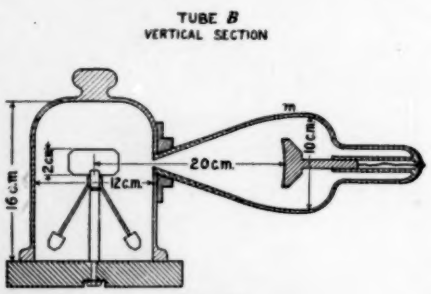


Fig. 2*b*.

2. Secondary rays from the walls of the tube were found to influence the readings of the electroscopes. According to rough measurements, the intensity of these secondary rays, as indicated by their ionizing power, amounted in certain cases to as much as 5 per cent. of the total intensity. This source of

error was almost entirely eliminated in tubes of both types by placing the kathode in side tubes, *m* and *n*, which were screened from the electroscopes by lead plates.

3. Since the Röntgen rays originate within the target, they undergo a certain amount of absorption within the target itself, and in general the amount of this absorption varies with the angle of emergence. This source of error was eliminated by making the target magnetically adjustable and always placing the normal so as to bisect the angle between the two measuring electroscopes and the target. The absorption within the target was thus necessarily the same for the two beams which were being compared.

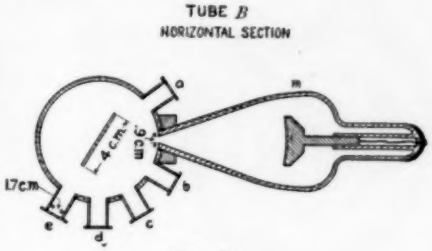
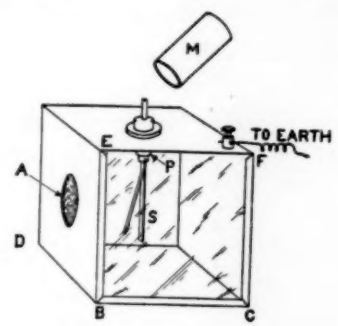


Fig. 2c.



BC=BD=BE=10 cm.
A, ARPERTURE OF CM DIAM. COVERED WITH RICE PAPER
P, AMBER PLUG HOLDING SUPPORTS FOR LEAF
BCFE, GLASS FRONT (SILVERED)
M, BRASS CAP

Fig. 3.

PROCEDURE.

In general, two electroscopes of the form shown in Fig. 3 were used.

These electroscopes were charged always to the same potential (about 480 volts) by means of a storage battery, and read in the usual way by micrometer microscopes. Their relative rates of discharge were obtained, in the earlier work, by placing them side by side at a considerable distance from an ordinary Röntgen ray tube, taking a discharge, then interchanging their positions and discharging again. Later it was found quite as satisfactory to place one on either side of tube *B* at the same angle to the kathode stream, the target being perpendicular to that stream. This gave a perfectly symmetrical arrangement of apparatus so that the rates of

discharge had to be proportional to the discharge constants of the two electroscopes. As a check, an interchange of position was also made, but it was found to be unnecessary. Both methods give consistent determinations of the ratio of the discharge constants of two electroscopes.

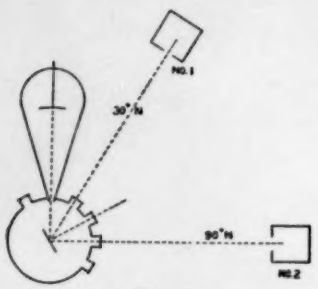


Fig. 4.

In the following discussion the angles mentioned will always be those formed between the line joining the electroscope and the target and the line joining the kathode and the target. In these experiments the kathode stream was directed from west to east; hence the letters N. and S. will be used to show on which side of the kathode stream the electroscope was placed. Thus, 30° N. will indicate a point on the north side of the tube, the angle between the kathode stream and the line from this point to the target being 30°.

PART I.

1. To determine whether there is a polarization two methods were used.

1st. (See Fig. 4.)

Electroscope No. 1 at 30° N.

Electroscope No. 2 at 90° N.

Normal to target at 60° N.

With various potentials the following results were obtained, using tube *B*.

TABLE I.

Discharge of No. 2 at 90° N.	Discharge of No. 1 at 30° N.	Per Cent. Polarization.	P.D.
16.6	13.5	18.7	11,000
14.95	13.0	13.0	16,000
15.7	13.7	13.0	16,200
26.5	22.3	16.0	13,000
16.8	14.0	16.8	13,000

In this case the ratio of the discharge constants of the electroscopes, which will hereafter be denoted simply by (No. 1/No. 2)

was 1.185. The actual discharges of electroscope No. 2 have been multiplied by this ratio to obtain the values given in the first column.

The "per cent. polarization" is obtained by dividing the numbers in the second column by those in the first, multiplying by 100 and then subtracting from 100.

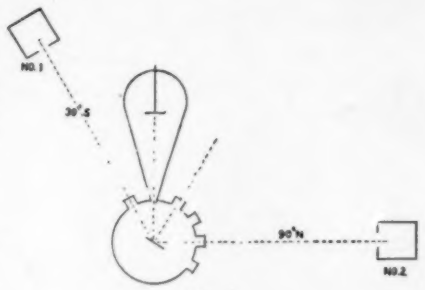


Fig. 5.

2d. (See Fig. 5.)

Electroscope No. 1 at 30° S.

Electroscope No. 2 at 90° N.

Normal to target at 30° N.

READINGS.

TABLE II.

Discharge of No. 2 at 90° N.	Discharge of No. 1 at 30° S.	Per Cent. Polarization.	P.D.
46.9	41.3	12.0	18,000
46.0	40.0	13.0	16,100
32.8	26.7	18.6	11,700
34.1	28.1	17.8	12,000
54.8	49.6	10.2	22,000
40.5	33.8	16.5	13,000

It is to be especially noted that the change in intensity between the 90° and 30° points is completely independent of the position of the normal to the target.

The direction of maximum intensity of the rays has therefore no connection with the angle of incidence of the kathode stream upon the target.

2 and 3. The questions as to whether there was a maximum at 90° and whether the change in intensity was symmetrical with respect to the 90° point, were investigated at the same time. Having determined the relative intensity at 90° and 30° in the preceding experiments, the following arrangement was used to compare the intensities in the 60° N. and 120° N. positions, first with each other and then with that in the 90° N. position.

1st. (See Fig. 6.)
Electroscope No. 1 at 30° S.
Electroscope No. 2 at 60° N.
Normal to target at 15° N.

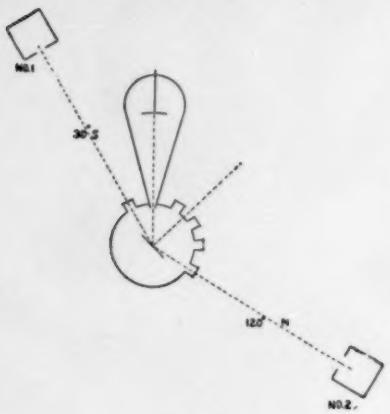


Fig. 6.

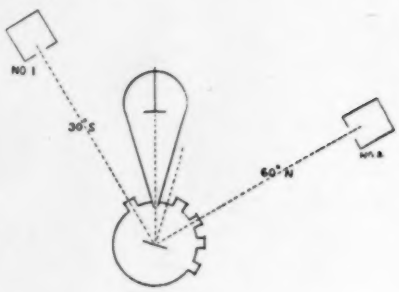


Fig. 7.

2d. (See Fig. 7.)
Electroscope No. 1 at 30° S.
Electroscope No. 2 at 120° N.
Normal to target at 45° N.

RESULTS.

TABLE III.

Discharge of No. 1 at 30° S.	Discharge of No. 2 at 120° N.	Per Cent. Decrease from No. 2 to No. 1.	P.D.
29.1	33.9	14.1	12,000
25.8	30.5	14.3	12,500
27.1	30.5	11.2	15,600
33.7	37.6	10.5	16,200
28.4	33.2 at 60° N.	14.5	11,600
26.4	30.6 " " "	13.8	12,200
35.5	39.7 " " "	10.5	15,000
32.6	36.3 " " "	10.1	15,200

Comparing the discharges taken at the same P.D. in the upper and lower halves of the above table, it is to be noticed that there is approximate symmetry, and referring to Table II. it will be seen that, between potentials of 16,000 and 12,000 volts, the intensity at

90° N. is greater than at either 60° N. or 120° N. by from 3 per cent. to 4 per cent.

4. To determine the effect of change of potential and gas pressure, the arrangement shown in Fig. 5 was used. The pressure was varied by means of the pump, and the P.D. varied accordingly. The results are represented graphically in plot A (Fig. *7a*). By per cent. polarization is meant here the per cent. change in intensity between 90° and 30°. In obtaining the data for plot A a great number of readings were taken, those in Tables I. and II. being merely samples. The procedure was to obtain the polarization with as great accuracy as possible at a P.D. at which the conditions were found most favorable for consistent results, and then to vary the potential. The discharge was very steady at a P.D. of 12,000 volts, and consequently about forty readings extending over several months were taken at this P.D. The mean polarization at 12,000 volts is slightly less than 18 per cent. The consistency of the results is indicated by the position of the points in the graph. (See Fig. *7a*.)

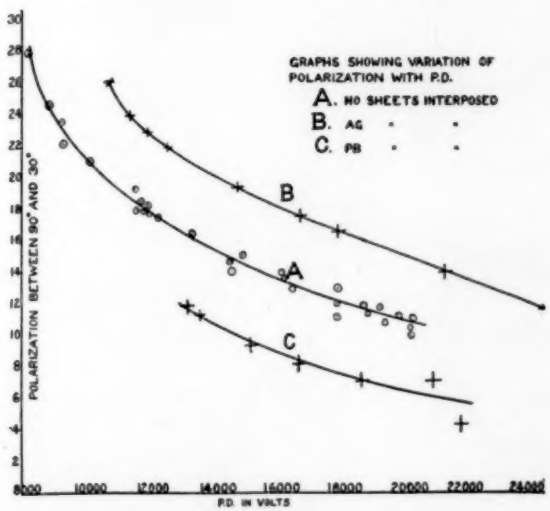


Fig. 7*a*.

5. To investigate the effect of absorbing sheets on the polarization, thin sheets of various materials were placed over the windows through which the rays passed to electroscopes No. 1 and No. 2, the

arrangement of apparatus and method of observation being the same as in 4. The sheets placed over the windows were as nearly equal in thickness as possible, but to eliminate the slight irregularities in thickness which were always found to exist, the sheets were interchanged and the mean readings used.

Table IV. shows a typical set of readings taken in order to obtain the relative rate of discharge of electroscope No. 1 with respect to No. 2. This relative rate is indicated in the tables as ratio No. 1/No. 2. This constant is of course changed whenever the electroscopes are changed or a leaf altered.

TABLE IV.

Discharge of No. 1 at 30° S.	Discharge of No. 2 at 30° N.	P.D.	Ratio, $\frac{\text{No. 1}}{\text{No. 2}}$.
55.4	45.4	13,200	1.220
52.8	43.0	13,200	1.227
65.2	53.8	15,000	1.230
67.5	55.5	14,400	1.217
67.0	55.3	13,800	1.212
38.0	31.1	12,000	1.223
41.5	33.9	11,700	1.225
			Mean, 1.222

The data obtained upon the effect of absorbing sheets on the polarization is shown in Tables V., VI., VII. and VIII., and in plots B and C (Fig. 7 *a*).

TABLE V.

Effect of interposing Ag sheets .100 mm. thick in path of beams.

Ratio, $\frac{\text{No. 1}}{\text{No. 2}} = 1.22$	Discharge of No. 1 at 30° S.	Discharge of No. 2 at 90° N.	No. 2 Times Ratio.	P.D.	Per Cent. Polarization.
Sheets interposed.	39.7	45.9		12,600	
Sheets interchanged.	44.9	42.4		12,600	
Total discharge.	84.4	88.3	107.7	12,600	21.8
Sheets removed.	62.8	58.6	71.6	16,000	13.6
Last reading reduced by plot A.[1]				12,600	16.8
Using Ag sheets .030 mm. thick. New electroscopes.					
Ratio, $\frac{\text{No. 1}}{\text{No. 2}} = 1.155$					
Sheets interposed.	38.3	42.3		12,000	
Sheets interchanged.	38.0	44.1		12,000	
Total discharge.	76.3	86.4	100.0	12,000	23.7
Sheets removed.	82.3	86.0	99.9	12,000	17.6
New leaf on electroscope No. 2. Same sheets as before.					

Ratio, $\frac{\text{No. 1}}{\text{No. 2}} = 1.20$					
Sheets interposed.	45.6	49.2		12,000	
Sheets interchanged.	45.9	49.0		12,000	
Total discharge.	91.5	98.2	118.0	12,000	22.5
Sheets removed.	53.1	53.5	62.2	12,000	17.3
Sheets interposed.	46.0	49.2		12,000	
Sheets interchanged.	43.6	49.1		12,000	
Total discharge.	89.6	98.3	118.0	12,000	23.4
Using Ag sheets .067 mm. thick.					
Sheets interposed.	53.9	58.0		12,000	
Sheets interchanged.	56.1	61.8		12,000	
Total discharge.	110.0	119.8	143.8	12,000	23.5
Sheets removed.	62.3	63.4	76.0	12,000	18.0

Increase in polarization caused by Ag sheets .100 mm. thick, 5.0 per cent.
Increase in polarization caused by Ag sheets .030 mm. thick, 5.4 per cent.
Increase in polarization caused by Ag sheets .067 mm. thick, 5.5 per cent.

TABLE VI.

Effect of interposing Pb sheets .038 mm. thick.

Ratio, $\frac{\text{No. 1}}{\text{No. 2}} = 1.12$	Discharge of No. 1 at 30° S.	Discharge of No. 2 at 90° N.	Discharge of No. 2 Times Ratio.	P.D.	Per Cent. Polarization.
Without sheets.	50.2	53.4	59.6	13,800	15.8
Sheets interposed.	42.0	38.3		13,800	
Sheets interchanged.	40.4	45.3		13,800	
Mean of last two observations.	41.2	41.8	46.8	13,800	11.9
Sheets removed.	48.2	51.2	57.3	13,800	15.9
Using Pb sheets .025 mm. thick.					
Sheets interposed.	40.0	43.1		14,100	
Sheets interchanged.	36.3	34.4		14,100	
Mean of last two observations.	38.2	38.7	43.4	14,100	11.6
Sheets removed.	61.6	63.9	71.6	14,400	14.0
Last reading reduced by plot A.				14,100	14.3

Decrease in polarization caused by Pb sheets .038 mm. thick, 4.0 per cent.
Decrease in polarization caused by Pb sheets .025 mm. thick, 2.7 per cent.

[1] By "reading reduced" is meant that the per cent. polarization at a given P.D. is reduced by means of plot A to a value corresponding to some other P.D., *i. e.*, the last reading in the above table was taken at a P.D. of 16,000 volts. The polarization obtained must be reduced to a value corresponding to 12,600 volts before comparisons can be made with the preceding data.

Plot C shows the effect of changing the P.D. when sheets of lead .05 mm. thick are interposed in the path of the beams to the two electroscopes. The probable error is rather large, due to the slow discharge of the electroscopes and the necessity of making considerable correction for natural leak.

TABLE VII.

Effect of interposing Sn sheets of .015 mm. thickness.

Ratio, $\frac{\text{No. 1}}{\text{No. 2}} = 1.144$	Discharge of No. 1 at 30° S.	Discharge of No. 2 at 90° N.	Discharge of No. 2 Times Ratio.	P.D.	Per Cent. Polarization.
Sheets interposed.	48.9	52.3		12,600	
Sheets interchanged.	50.0	53.4		12,600	
Total discharge.	98.9	105.7	120.9	12,600	18.2
Four discharges, sheets removed.	193.3	203.8	233.0	12,600	17.0
Sheets increased to .045 mm. thickness.					
Sheets interposed.	46.9	51.8		14,100	
Sheets interchanged.	45.3	47.6		14,100	
Total discharge.	92.2	99.4	113.7	14,100	19.0

In the first of the above cases, an increase in polarization of 1.2 per cent. is shown when the two windows leading to the electroscopes are covered with tin of .015 mm. thickness. On making the thickness of tin three times as great, the increase became about 3.9 per cent. This was found to increase but slightly with the further addition of sheets. With sheets of .060 mm. thickness, the increase seemed to coincide with that caused by silver, and no change was observed with a greater thickness. With the thickness greater than .045, however, the results became less reliable, because of the long time required for a discharge.

In none of the above cases is there a change which is larger than the experimental error.

From the four preceding tables it is seen that, of the substances tried, tin, silver and lead caused a change in the polarization. The maximum effect of tin and silver, as well as the change in polarization with variation of P.D., is shown in plot B, and the effect of lead sheets of .05 mm. thickness in plot C. The effect on the polariza-

tion of increasing the thickness of the absorbing sheets is shown in Tables V., VI. and VII.

TABLE VIII.

Effect of interposing paper 1.0 *mm. thick.*

Ratio, $\frac{\text{No. 1}}{\text{No. 2}} = 1.22$	Discharge of No. 1 at 30° S.	Discharge of No. 2 at 90° N.	Discharge of No. 2 Times Ratio.	P.D.	Per Cent. Polarization.
Sheets interposed.	26.8	26.0		12,600	
Sheets interchanged.	30.0	31.3		12,600	
Weighted total discharge	53.0	53.4	65.1	12,600	18.7
Effect of interposing paper 3.0 *mm. thick.*					
Sheets interposed.	44.7	44.7		12,000	
Sheets interchanged.	34.0	33.7		12,000	
Weighted total discharge.	68.0	67.7	82.4	12,000	17.5
Effect of interposing glass sheets respectively .772 *and* .762 *mm. thick.*					
Sheets interposed.	41.6	41.8		12,000	
Sheets interchanged.	44.4	44.1		12.000	
Total discharge.	86.0	85.9	104.8	12,000	18.0
Sheets removed.	44.0	43.7	53.3	12,000	17.9
Effect of interposing Al sheets .04 *mm. thick.*					
Ratio, $\frac{\text{No. 1}}{\text{No. 2}} = 1.12$					
Sheets interposed.	51.8	55.0		13,800	
Sheets interchanged.	52.1	55.5		13,200	
Mean of last two observations.	51.9	55.3	61.9	13,500	16.2
Sheets removed.	48.5	51.4		12,600	
" "	51.1	53.3		12,300	
" "	53.0	56.4		12,600	
" "	44.6	46.5		12,600	
Total discharge.	194.2	207.6	232.5	12,500	16.5
Last reading reduced by plot A.				13,500	16.0

Two remarkable results are noticed in these tables: (1) that lead has an effect on the polarization opposite to that of tin and silver, (2) that in the cases of tin and silver, a maximum effect is obtained at a given thickness of sheets and no further increase of polarization is produced by the use of thicker sheets.

No limit to the decrease in the polarization produced by lead was reached.

Discussion of Results.

The results of 1, 2, 3 and 4, made by direct observation on the primary rays, confirm completely the conclusions regarding the polarization of the primary rays arrived at by Barkla, and recently

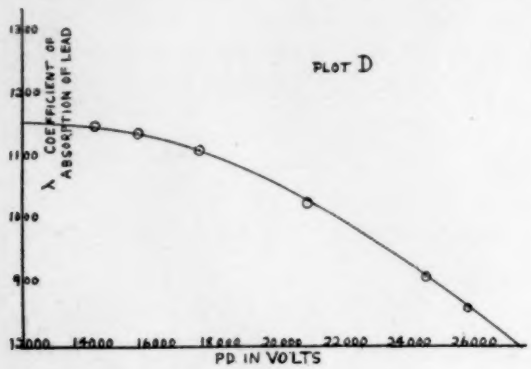


Fig. 7*b*.

confirmed by Haga, from a study of observations on the secondary rays. They indicate that Röntgen rays consist, in part at least, of ether pulses such as would be caused by accelerations given to kathode ray particles on entering a target.

In explanation of the fact that the polarization is decreased when the rays pass through lead and increased when they pass through tin and silver, and of the further fact that the polarization cannot be increased beyond a certain limit by using increasing thicknesses of silver and tin, the following suggestions are offered.

Secondary rays are set up when Röntgen rays strike or pass through a metal plate.[1] Since the rays under consideration have originated within the target and in emerging pass through its upper layers, it is to be expected that these rays would consist of a mixture of primary and secondary rays.

According to the work of Barkla[2] the secondary rays from most

[1] G. C. Barkla, Phil. Mag., 11, pp. 812–828, 1906.

[2] Barkla and Sadler, Phil. Mag., 14, pp. 408–422, 1907. G. C. Barkla, Phil. Mag., 16, pp. 550–684, 1908.

metals except tin and silver, have the same intensity in all directions, *i. e.*, are unpolarized. Therefore if the secondary rays from the lead target emerge from the tube and cause ionization in the electroscopes, the polarization of the total beam from the target will be less than if secondary lead rays were not present. In case the windows are covered with sheets of any material which has a different absorption coefficient for the two types of rays, a change in the amount of polarization between 90° and 30° will take place.

Secondary rays are particularly penetrating for the same substance as that of the plate in which they are generated.[1] Hence, if they exist outside the tube, it is not surprising that lead, of which all the targets used in these experiments are made, absorbs the secondary rays less strongly than the primary, and hence that lead decreases the polarization, the primary rays alone being originally polarized.

Since paper, glass and aluminium apparently do not change the polarization, it is probable that these substances, at least at the P.D. at which the experiments were made, have about the same absorption for secondary and primary rays from lead.

Silver and tin seem to have a much greater absorption for the secondary rays from lead than for the primary, and if this be true, an upper limit to the polarization would be reached when the secondary rays are practically all absorbed. The ratio of the intensity of these secondary rays to the primary rays at a given P.D. could then be calculated if it be assumed that the secondary rays are completely unpolarized. Thus let

I_{p90} = intensity of primary at 90°,
I_{p30} = " " " " 30°,
I_s = " " secondary.

Let

$$\frac{I_{p90}}{I_{p30}} = a.$$

Let

$$\frac{I_{p90} + I_s}{I_{p30} + I_s} = b.$$

[1] G. W. C. Kaye, Roy. Soc. Phil. Trans., Ser. A, 209, pp. 123–151, 1908. G. W. C. Kaye, Cambridge Phil. Soc. Proc., 14, pp. 236–245, 1907. See also footnote 2.

Solving

$$I_s = I_{p90}\left(\frac{a-b}{a(b-1)}\right).$$

If plot B represents the condition in which the secondary rays have all been absorbed, a can be found at once for any P.D. from plot B; b can of course be found from plot A.

In the specific case when P.D. = 12,000 volts,

$$a \doteqdot 1.30, \quad b \doteqdot 1.22$$
$$\therefore I_s = .27 I_{p90}$$

When P.D. = 22,000 volts,

$$a \doteqdot 1.16, \quad b \doteqdot 1.11$$
$$\therefore I_s = .40 I_{p90}$$

On the above hypothesis, then, an idea is obtained of the relative intensity at 90° of the primary and secondary radiation emerging from a tube provided with a lead target.

Unfortunately it was not possible to obtain reliable determinations of the P.D. beyond the points indicated in the plots, owing to the discharge through the tube becoming unsteady. But by using an induction coil, when the tube was hard the polarization was reduced nearly to zero. The curves must come very near the axis at a P.D. probably between 40,000 and 45,000 volts, which means that the X-rays originating under a P.D. larger than 45,000 volts probably show no polarization.

SUMMARY OF RESULTS IN PART I.

1. A polarization exists and is independent of the position of the normal to the target, as shown by comparing the results of the two methods used in 1.

2 and 3. The maximum intensity is, within experimental error, in the plane through the target normal to the kathode ray stream, and the intensity falls off symmetrically on either side of this plane.

4. The polarization is affected by the P.D. alone and increases with a decrease of P.D., as is to be expected from the ether pulse theory.

5. The interposition of sheets of silver and tin causes an increase in polarization which reaches the same upper limit for both metals. Lead decreases the polarization but no lower limit was observed. Aluminium, paper and glass cause very slight change if any in the polarization.

All the observed results are completely explained if it be assumed that the ordinary X-ray beam consists of a mixture of primary and secondary rays originating in the target, and that the secondary rays are completely unpolarized.

Part II.

6 and 7. Absorption Coefficients and Variation of these Coefficients with the P.D.

(*a*) *The Coefficient of Absorption of Lead.*

The following arrangement was used in determining the coefficients of absorption of lead and tin. (See Fig. 8.)

Electroscope No. 1 at 30° S.
" " 2 " 30° N.
Normal to target at 0°.

Sheets of the substance under investigation were placed over one of the windows, and the per cent. decrease in discharge rate of the corresponding electroscope was taken as a measure of the absorption.

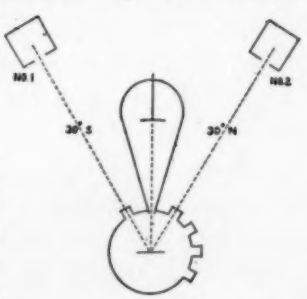


Fig. 8.

The thickness was determined by weighing the sheets, measuring the area and assuming the density to be that found in tables. Since relative intensity only is measured, density is not an important point provided it is the same for the sheets used in a given experiment. The sheets were cut from the same large sheet. In the case of lead the sheets were rolled from the same strip of lead of which the target was made.

Table IX. gives both the coefficient of absorption at a given P.D. as calculated from sheets of lead of various thicknesses and the

change in coefficient of absorption with change of P.D. In this table λx is obtained from the equation $I = I_0 e^{-\lambda x}$ where I_0 is the intensity of the beam before, and I after the sheet under consideration is interposed, and where x is the thickness of the sheet in centimeters.

TABLE IX.

Absorption of Pb. Ratio, $\frac{No.\ 2}{No.\ 1} = 1.096$. *Lead sheet placed over window leading to No. 2.*

No. 1 at 30° S.	No. 1 Times Ratio.	No. 2 at 30° N.	Thickness of Pb in cms.	Per Cent. Remaining After Absorption.	P.D.	λX	λ
113.2	124.0	8.8	.00238	7.1	14,300	2.65	1120
104 0	114.0	21.3	.00147	18.7	13,700	1.675	1139
102.8	112.7	50.5	.00070	44.9	14,300	.800	1140
107.6	117.9	65.9	.00051	56.0	14,300	.580	1137
Sheet transferred to window leading to No. 1. Ratio, $\frac{No.\ 2}{No.\ 1} = 1.100$.							
19.5	21.6	61.5	.000909	35.1	14,300	1.047	1152
20.5	22.7	64.3	.000909	35.3	15,600	1.040	1144
22.2	24.6	67.3	.000909	36.4	17,500	1.010	1116
22.6	25.0	63.8	.000909	39.2	21,000	.935	1029
18.5	20.4	47.6	.000909	43.7	24,800	.828	911
24.6	27.2	59.8	.000909	43.8	24,800	.825	909
22.7	25.1	55.0	.000909	45.7	26,000	.782	860

The coefficient λ seems to be very nearly constant at a given P.D., λ perhaps decreasing slightly in the case of the thickest sheet used. At first sight this may seem to be inconsistent with the hypothesis, set up in Part I., of complex radiations emitted by the lead target. The absorption coefficients of lead, however, appear to be so nearly the same for the two radiations that in order to show an appreciable decrease in polarization in the experiments of Part I., it was necessary to use lead sheets of greater thickness than any of these in the tables.

The values of the coefficient of absorption for lead at various potentials are shown graphically in plot D.

(*b*) *The Coefficient of Absorption of Tin.*

In a similar way the following data with regard to the coefficient of absorption of tin was obtained.

TABLE X.

Absorption of Sn. Ratio, $\frac{No.\ 2}{No.\ 1} = 1.100$

No. 1 at 30° S.	No. 1 Times Ratio.	No. 2 at 30° N.	Thickness of Sn in cms.	Per Cent. Remaining After Absorption	P.D.	λX	λ
59.6	65.6	39.0	.00126	59.5	15,600	.519	412
110.4	121.4	43.5	.00259	35.9	15,600	1.030	395
112.3	123.5	27.0	.00399	21.9	15,600	1.519	381
177.4	195.1	27.5	.00521	14.1	15,600	1.959	376

It appears from this table that tin differs from lead in not showing a constant coefficient of absorption at a given P.D.

Seitz [1] has found that beyond a given thickness (.0177 mm.) tin shows a constant coefficient of absorption. The above data are not sufficiently extended to enable one to draw that conclusion, but it shows clearly that the change in coefficient grows rapidly smaller as thicker sheets are used. This agrees with the results obtained in Part I. as to the effect of Sn on the polarization.

(*c*) *The Coefficient of Absorption of Silver.*

The absorption of a given sheet of silver .030 mm. thick at 30° S. was compared with its absorption at 90° N. The arrangement is the same as in Fig. 5. The following table gives the results.

TABLE XI.

Absorption of Ag. Ratio, $\frac{No.\ 2}{No.\ 1} = 1.295$. *Ag sheet .030 mm. thick placed over window leading to No. 2.*

No. 1 at 30° S.	No. 1 Times Ratio.	No. 2 at 90° N.	Per Cent. Remaining After Absorption.	P.D.
101.1	130.8	31.7	24.2	14,000
Sheet transferred to window leading to No. 1.				
22.7	29.4	131.5	22.4	14,000

The fact that the absorption is greater at 30° S. than at 90° N. fully confirms the results obtained in Part I. in regard to the effect of silver sheets on the polarization.

[1] W. Seitz, Ann. d. Physik, 27, 2, pp. 301–310, Oct. 15, 1908.

8. Determination of the Mean Depth at Which X-Rays Originate.

In determining the polarization in Part I. it will be remembered that the effect of absorption within the target was eliminated by placing the normal to the target midway between the two electroscopes.

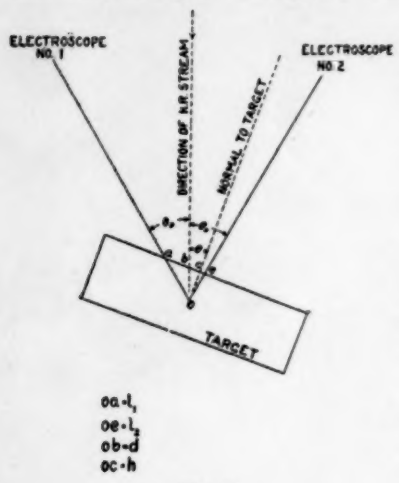


Fig. 9.

If the normal to the target is not midway between the electroscopes, the rays from a given point in the target have to pass through more lead in going to one electroscope than to the other. (See Fig. 9.)

Let o (Fig. 9) be the source of some ether pulse.

Let $l_1 - l_2 = x$, the excess of lead, which the pulse has to traverse in passing to electroscope No. 1, over that which it traverses in passing to No. 2.

Let d be the distance from o to the point at which the kathode ray particle enters the target.

Let h be the perpendicular distance from o to the surface of the target.

Let θ_0 be the angle which the lines from the electroscopes to the target make with the kathode ray stream.

Let θ be the angle which the normal to the target makes with the kathode ray stream.

Then

$$x = h\left(\frac{1}{\cos(\theta_0 + \theta)} - \frac{1}{\cos(\theta_0 - \theta)}\right).$$

But

$$h = d\cos\theta,$$

$$\therefore x = d\cos\theta\left(\frac{1}{\cos(\theta_0 + \theta)} - \frac{1}{\cos(\theta_0 - \theta)}\right).$$

Consider two positions, θ_1 and θ_2 of the normal to the target such that for the first $\theta = \theta_1$, for the second $\theta = \theta_2$.

Then

$$\frac{x_1}{x_2} = \frac{d_1 \cos\theta_1 \left(\frac{1}{\cos(\theta_0 + \theta_1)} - \frac{1}{\cos(\theta_0 - \theta_1)} \right)}{d_2 \cos\theta_2 \left(\frac{1}{\cos(\theta_0 + \theta_2)} - \frac{1}{\cos(\theta_0 - \theta_2)} \right)}.$$

For brevity let the above be written:

$$(1) \qquad \frac{x_1}{x_2} = \frac{d_1 \cdot F(\theta_0, \theta_1)}{d_2 \cdot F(\theta_0, \theta_2)}.$$

Now let the intensity of the ray at the electroscope No. 2 be I_0, and assume that the intensity at No. 1 is $I_0 e^{-\lambda x}$, where $x = l_1 - l_2$ and λ may be called the apparent coefficient of absorption at a given value of x.

Then $I_0 e^{-\lambda x}/I_0 = e^{-\lambda x} = a$ where a is some constant given by the discharges obtained in the electroscopes.

Then $\lambda x = \log 1/a = A$, another constant.

Then, for particular values of θ,

$$\lambda_1 x_1 = A_1, \quad \lambda_2 x_2 = A_2, \quad \text{etc.}$$

Or

$$(2) \qquad \frac{x_1}{x_2} = \frac{\lambda_2}{\lambda_1} \cdot \frac{A_1}{A_2}.$$

A comparison of 1 and 2 shows that

$$(3) \qquad \frac{d_1 \cdot F(\theta_0, \theta_1)}{d_2 \cdot F(\theta_0, \theta_2)} = \frac{\lambda_2}{\lambda_1} \cdot \frac{A_1}{A_2}.$$

Table XII. shows that experimentally

$$\frac{F(\theta_0, \theta_1)}{F(\theta_0, \theta_2)} = \frac{A_1}{A_2},$$

$$\therefore \frac{d_1}{d_2} = \frac{\lambda_2}{\lambda_1} \quad \text{or} \quad d_1\lambda_1 = d_2\lambda_2, \text{ etc.}$$

Outside the tube, λ for lead is found to be a constant and the above indicates that λ inside the tube is a constant also unless d, the mean depth of penetration of the kathode ray stream in the target,

varies in such a way as to make the above relation hold when the target is turned through various angles. The last is very improbable. Indeed it would have been very reasonable to assume at the start that d was a constant. Hence the conclusion is reached that λ within the tube is constant.

Further, since the value of λ for lead is a constant when found by direct observation outside the tube, and appears to be so within the target, it will be assumed that the value of λ is the same in both cases.

The following table gives one of the sets of readings taken in the determination of the absorption within the target.

TABLE XII.

$\theta_0 = 30°$. *Ratio*, $\frac{No.\ 1}{No.\ 2} = .910$

No. 1 at 30° S.	No. 2 at 30° N.	No. 2 Times Ratio.	θ Position of Normal to Target.	P.D.	$F(\theta_0, \theta)$	a Per Cent.	Mean a Reduced to 14,000 Volts. See Topic 9.	
55.8	60.0	54.6	θ_1 15° S.	15,600	.366	97.8		
51.7	55.5	50.4	15° S.	16,500	.366	97.7		
52.4	58.8	53.5	15° N.	16,500	.366	97.9	a_1	A_1
50.9	56.9	51.8	15° N.	14,000	.366	98.6	98.3 %	.017
48.2	55.4	50.4	θ_2 30° N.	14,000	.866	95.6		
46.8	53.7	48.9	30° N.	14,300	.866	95.7		
49.7	52.8	48.0	30° S.	14,600	.866	96.1	a_2	A_2
55.0	58.0	52.8	30° S.	14,000	.866	96.0	95.9 %	.042
49.3	49.0	44.6	θ_3 45° S.	15,000	2.00	90.5		
51.4	51.0	46.6	45° S.	14,300	2.00	90.7	a_3	A_3
45.5	55.9	50.9	45° N.	14,600	2.00	89.4	90.9 %	.095

From the above table

$$\frac{F(\theta_0, \theta_1)}{F(\theta_0, \theta_2)} = .424, \quad \frac{A_1}{A_2} = .40$$

$$\frac{F(\theta_0, \theta_1)}{F(\theta_0, \theta_3)} = .183, \quad \frac{A_1}{A_3} = .18$$

$$\frac{F(\theta_0, \theta_2)}{F(\theta_0, \theta_3)} = .433, \quad \frac{A_2}{A_3} = .44$$

These results furnish excellent confirmation of the assertion made concerning equation (3).

The calculation of d is then made as follows:

From Table XII. it will be seen that when

$$\theta = 45°,\ A_3 = .095 = \lambda x_3,$$

$$\lambda \text{ from plot D} \doteqdot 1150,$$

$$\therefore x_3 \doteqdot \frac{.095}{1150} = .000083 \text{ cm.},$$

$$\therefore d = .000041 \text{ cm.}$$

Further, when $\theta = 30°$, $x_2 = .000037$ cm., $d = .000043$ cm.; and when $\theta = 15°$, $x_1 = .000015$ cm., $d = .000041$ cm.

Or, mean $d \doteqdot 4.2 \times 10^{-5}$ cm. at 14,000 volts.

9. Variation of Mean Depth with P.D.

To obtain the variation of this mean depth with the P.D. the apparatus was adjusted once for all, with the target turned at any convenient angle, and discharges of the electroscopes were taken at various potentials.

The following table illustrates the results obtained.

Table XIII.

$\theta_0 = 30°$. *Ratio*, $\frac{No.\ 1}{No.\ 2} = .905$

No. 1 at 30° S.	No. 2 at 30° N.	No. 2 Times Ratio.	θ Position of Normal to Target.	P.D.	$F(\theta_0, \theta)$	Mean a.	Mean A.	Mean x.	Mean d.
55.0	64.2	58.1	30° N.	21,000	.866			$\frac{.056}{1025} =$	
55.6	58.1	52.6	30° S.	21,600	.866	94.4 %	.056	5.5×10^{-5}	6.4×10^{-5}
				21,300	.866			cm.	

This table gives the depth at 21,300 volts. The depth at 14,000 volts is given in the preceding table. The only difference in the two tables is in the P.D.

The effect on the computed value of the mean depth, of covering the windows leading to the electroscopes with similar silver sheets, is shown in the following table.

TABLE XIV.

$\theta_0 = 30°$. *Ratio,* $\frac{No.\ 1}{No.\ 2} = .895$. *Thickness of Ag. sheets* .030 *mm.*

No. 1 at 30° S.	No. 2 at 30° N.	No. 2 Times Ratio.	θ Position of Normal to Target.	P.D.	$F(\theta_0, \theta)$	Mean a.	Mean A.		Mean d.
55.0	63.9	57.2	30° N.	15,500	8.66				
43.1	50.1	45.6	30° N.	16,200	8.66			$x = \frac{.042}{1140} =$	4.3×10^{-5} cm.
51.7	56.0	50.1	30° S.	15,900	8.66		.042 at	3.7×10^{-5}	
51.7	55.8	49.9	30° S.	15,900	8.66	95.9	15,900	cm.	
50.2	53.9	48.1	30° S.	15,900	8.66				
49.0	51.8	46.4	30° S.	22,200	8.66				
49.5	58.0	51.9	30° N.	21,000	8.66			$x = \frac{.052}{1020} =$	5.9×10^{-5} cm.
45.3	53.3	47.7	30° N.	22,200	8.66	94.9	.052 at	5.1×10^{-5}	
49.7	58.1	52.2	30° N.	21,000	8.66		21,500	cm.	
44.9	52.8	47.3	30° N.	22,200	8.66				

From Tables XII. and XIII.

$$\frac{4.2 \times 10^{-5}}{6.4 \times 10^{-5}} = .65, \qquad \frac{14,000}{21,300} = .658$$

And from Table XIV.

$$\frac{4.3 \times 10^{-5}}{5.9 \times 10^{-5}} = .73, \qquad \frac{15,900}{21,500} = .740$$

The difference between the ratio of the depths and the ratio o he potentials is not greater than 2 per cent. in either case.

The last three tables lead to the conclusion that, within experimental error, *the mean depth in the target at which the Röntgen rays originate is proportional to the P.D.*

Further, it is to be noted that the interposition of silver sheets lessens the value ot this mean depth, at a given P.D., as is shown by a comparison of Table XIV. with XII. and XIII.

Discussion of Part II.

Nearly all the data in Part II. was obtained with a view to finding the mean depth in the target at which Röntgen rays originate. Incidentally some of the conclusions of Part I. were confirmed. Thus it was found by direct experiment that the coefficients of absorption of silver, tin and lead do not depend upon the P.D. alone, but decrease if the thickness is increased, the change taking place, however, very slowly in the case of lead. Furthermore, the absorption of a silver sheet at 90° was found to be less than at 30°.

The most important results of Part II., however, are (1) the proof that the mean depth in the target at which Röntgen rays, produced at a given P.D., originate, is a perfectly definite quantity and quite independent of the angle at which the kathode stream strikes the target; (2) the determination of the relation between this depth and the potential; and (3) the determination of this mean depth when the rays under investigation have passed through absorbing silver sheets.

If the hypothesis be adopted that the X-ray beam consists of a mixture of primary and secondary rays, the latter of which are more readily absorbed by silver than are the former, it is easy to see why the mean depth decreases when the measurements upon it are made through silver sheets. For since the primary X-rays are much more penetrating than the kathode rays which give rise to them, the secondary rays produced by these primary X-rays will obviously come from greater depths than do the primary rays themselves; and hence when the secondary rays from the target are absorbed, the mean depth of the emergent rays is smaller than before they were absorbed.

These considerations make possible the calculation of the depth within a lead target at which complete scattering of the entering kathode rays occurs. Thus it was shown in Part I. that the polarization is practically zero above about 45,000 volts. If then the secondary rays are absorbed by silver sheets and measurements or calculations made of the mean depth at which the primary rays originate for any P.D. above that at which the polarization of the primary has become inappreciable, that depth is itself the depth at

which complete scattering[1] occurs for this P.D. For, a completely unpolarized beam is one in which the number of pulses produced by the kathode beam before complete scattering has occurred is negligible in comparison with those produced after complete scattering. Hence, for potentials at which there is no polarization of the primary, the mean depth of emergence of the primary is the depth of complete scattering. It will be seen from Table XIV. that when the secondary rays were absorbed by silver the d corresponding to a potential of 21,500 volts, for example, is 5.9×10^{-5} cm. Since d is proportional to the P.D. at say 90,000 volts (which is far above the potential at which there is polarization) d would be

$$5.9 \times 10^{-5} \times \frac{90{,}000}{21{,}500} = 2.5 \times 10^{-4} \text{ cm.}$$

Crowther[2] has determined this thickness for complete scattering in the case of β rays and from his results the depth for complete scattering in gold at a velocity of 1.6×10^{10} (which corresponds to a P.D. of 90,000 volts according to Lorentz's formula) is found to be 2.0×10^{-4} cm.

That gold and lead should have the depth for complete scattering at a given P.D. so nearly the same is not surprising in view of their similarity in atomic weights. At any rate the comparison makes it evident that the two entirely different methods give results of the same order of magnitude.

SUMMARY OF RESULTS IN PART II.

6. The coefficient of absorption for lead is a constant, within experimental error, at a P.D. of 14,000 volts. The coefficient of absorption of tin decreases slightly as thicker sheets are used in determining it. Silver shows a different absorption at 90° from that shown at 30°.

7. The coefficient of absorption decreases as the hardness of the tube increases.

[1] By the depth of complete scattering is meant the depth at which on the average, as many of the kathode particles which have entered the target are suffering accelerations in one direction as in any other.

[2] Scattering of β Rays by Matter, J. A. Crowther, Roy. Soc. Proc., Ser. A, 80, pp. 186–206, March 5, 1908.

8 and 9. The mean depth at which the Röntgen rays originate in a lead target is proportional to the P.D. and at a P.D. of 21,500 volts is 5.9×10^{-5} cm. which is of the order of the wave-length of sodium light.

The thickness of lead required to produce complete scattering of an X-ray beam is proportional to the P.D. and at a P.D. of 90,000 volts is 2.5×10^{-4} cm.

In conclusion the author wishes to express his thanks to Professor Michelson and the staff of the Ryerson Laboratory, particularly to Professor Millikan, under whose direction and with whose continual assistance this research has been conducted.

UNIVERSITY OF CHICAGO,
July 31, 1909.

PROCEEDINGS

OF THE

AMERICAN PHYSICAL SOCIETY.

MINUTES OF THE FORTY-NINTH MEETING.

A REGULAR meeting of the Physical Society was held in the new Physical Laboratory of the University of Illinois, Urbana, Illinois, on Saturday, November 27, 1909. President Henry Crew presided.

The following papers were presented:

1. Preparation and Properties of the Heusler Alloys. A. A. KNOWLTON.

2. Magnetic Properties of Heusler Alloys. A. A. KNOWLTON and O. G. CLIFFORD.

3. The Magnetic Properties of the Heusler Alloys. E. B. STEPHENSON.

4. The Effect of Temperature on the Magnetic Properties of Electrolytic Iron. EARLE M. TERRY.

5. The Point Discharge in Air for Pressures Greater than Atmospheric. O. A. GAGE.

6. On the Mechanical Equivalent of Heat by a Porous Plug Method. J. R. ROEBUCK.

7. The Elastic Properties of Platinum-Iridium Wire. KARL E. GUTHE.

8. An Apparatus for Measuring Sound. F. R. WATSON.

9. Polarization of Cadmium Cells. R. R. RAMSEY.

10. A Method for Determining the Optical Constants of Metals Applicable to Measurements in the Infra-red. L. R. INGERSOLL.

11. The Absolute Values of the Moments of Elementary Magnets. JAKOB KUNZ.

12. An Apparatus for Studying Moment of Inertia. C. M. SMITH.

13. Some Curious Phenomena Observed in Connection with Melde's Experiment. J. S. STOKES.

14. "Porous Plug" and "Free Expansion" Effects under varying Pressure. A. G. WORTHING.

15. The Absorption of X-Rays an Additive Property. R. A. MILLIKAN and E. J. MOORE.

16. A Comparison of the Echelon and Diffraction Gratings. H. B. LEMON.

17. The Value of e by Wilson's Method. L. BEGEMAN.
18. The Flow of Energy in an Interference Field. MAX MASON.
19. The Stark Effect with Canal Rays. G. S. FULCHER.

ERNEST MERRITT,
Secretary.

PREPARATION AND PROPERTIES OF THE HEUSLER ALLOYS.[1]

BY A. A. KNOWLTON.

THE fact that practically all workers who had studied these alloys found occasion to complain of the mechanical qualities of their specimens led the writer to undertake a study of the precautions necessary in order to reduce these difficulties to a minimum. The essential features of the treatment finally adopted were: prolonged heating, the use of nearly silica-free crucibles, casting in hot molds and annealing to a temperature of 250° C. The prolonged heating is necessary when preparing the Cu-Mn alloys in order to insure a uniform mixture. Casting and remelting somewhat aids the process. The bath should be in the molten state for at least two hours for satisfactory results. Graphite crucibles must be used because of the rapid action of manganese upon silica. Even with the best graphite crucibles from one tenth to one per cent. of Si is found in the alloy. The hardness and brittleness is very greatly increased if the Si present amounts to more than one half per cent. A considerable advantage in this respect might be gained by the use of magnesium oxide crucibles. The castings were made in carbon moulds heated to a temperature somewhat above the melting point of the alloys and were packed in asbestos so as to cool to 250° C. in about an hour. From that temperature they were chilled by quenching. This procedure was adopted because it was found that annealing greatly improved the mechanical qualities while the magnetic qualities of specimens annealed to temperatures below 200° were usually very poor. Rods 14 cm. long and 8 mm. in diameter made in this way were of good quality both mechanically and magnetically.

From a very large number of castings made, fourteen were selected for examination. The electrical resistance, temperature coefficient of resistance, magnetic properties and change of magnetic properties with heating were studied and compared with the result of a microscopic study of the crystalline structure.

Previous observers have reported specimens which showed strongly marked minima in the resistance temperature curves. None of the writer's specimens showed any such effect. The curves are in all cases

[1] Abstract of a paper presented at the Urbana meeting of the Physical Society, November 27, 1909.

straight lines differing from those for the pure metals only in their slope, and in the fact that at high temperatures a large permanent decrease in resistance takes place as in many other alloys. This change, which may amount to as much as 40 per cent. of the original value, takes place slowly at ordinary temperature and is always accompanied by an improvement in the crystalline structure. Any change which is injurious to the crystalline structure causes a marked increase in the resistance. The magnetization reached a saturation value of about 400 c.g.s in the best specimens. The field required for saturation varied considerably with different specimens. No simple relation seems to hold between the proportions of any two constituents and the magnetic properties. The part played by the copper in the alloy appears to be much more important than has been generally assumed. Both the maximum induction and the transformation temperature are greatly affected by the per cent. of copper present. In fact the transformation temperature appears to be almost wholly dependent upon the ratio of copper to manganese. By varying this proportion simply by the addition of copper it was possible to make specimens with transformation points from 0° C. to 300° C.

The results of the heat treatments are substantially the same as have been found by other observers. Transformation from the magnetic to the non-magnetic state extends over a range of about 50° C. in all cases, although the absolute value of this temperature depends upon the composition of the specimen. Annealing at the lower limit of transformation is injurious to the magnetic quality. Annealing at the upper limit improves the magnetic quality. Since the lower and upper limits for average specimens are 220° and 270° this explains the good results obtained by quenching from 250°.

Microscopically the alloy is found to contain three sorts of crystals sharply differentiated from one another. One type is seemingly unaffected by the reagent (a mixture of HCl and $FeCl_3$) and retains its polished surface, one is colored nearly black and the third which appears to partake of the nature of a matrix is yellowish in color. The unaffected crystals are those which possess the magnetic properties as shown by the fact that no specimens from which they were lacking were found to be magnetic while whenever they were present a fair estimate of the value of I at saturation could be made by visual inspection. The area covered by the unaffected crystals was measured in a considerable number of cases and compared with the magnetization. Within the limits of error of the measurement the saturation value of I is directly proportional to the area of the crystals of this sort.

Specimen no. 14, Cu 72.2 per cent., Mn 17.4 per cent., Al 10.3 per cent., forms an exception to the above rule. On the basis of unaffected crystal area, its saturation value of I should be about 225 c.g.s. As a

matter of fact the specimen appears not to be appreciably magnetic until cooled to 0° C. This seems to indicate that while the structure of the crystals and the magnetic quality are very closely related, the crystal is not itself the magnetic unit. The difference whatever it may be between no. 14, or in fact any other specimen, in the magnetic state and the non-magnetic state would appear to be due to exceedingly slight differences in molecular grouping since very careful experiments on a number of other specimens have failed to detect any phenomena of the nature of recalesence. It appears certain that the ferro-magnetism of the Heusler alloys depends upon molecular grouping and is therefore a crystaline rather than a molecular property.

PHYSICAL LABORATORY,
UNIVERSITY OF UTAH,
November 6, 1909.

MAGNETIC PROPERTIES OF HEUSLER ALLOYS.[1]

BY A. A. KNOWLTON AND O. C. CLIFFORD.

DURING the work with these alloys carried on by one of the writers, it became apparent that a further investigation of the dependence of properties on composition was desirable and also that in spite of the extensive work done by others there were many points in relation to hysteresis losses still little understood. For testing a considerable number of rings, mostly of low aluminum content were prepared. These rings were prepared and cast with the precautions outlined in a previous paper except that in some cases the rings were quenched from a high temperature in order to investigate the effect of this procedure. As was to be expected, the rings so treated proved very unsatisfactory from a mechanical standpoint and in most cases broke while being ground. The rings were ground to uniform dimensions, wound with 864 turns of no. 22 copper wire and a secondary of 100 turns and tested by the step by step method. For heating purposes a bath containing about a gallon and a half of gas engine cylinder oil with mechanical stirring device was heated over a gas flame. Seven specimens running from 67.8 per cent. Cu, 27.8 per cent. Mn, 4.4 per cent. Al to 60.3 per cent. Cu, 25.4 per cent. Mn, 14.3 per cent. Al, were tested. Hysteresis curves were taken at 0°, room temperatures, and at several selected temperatures up to transformation. At room temperature the specimens showed wide variations in quality. Ring number one which was cast from scrap many times remelted was by far the best. Since there does not appear to be adequate cause for this either in composition or in heat treatment it is probably largely due

[1] Abstract of a paper presented at the Urbana meeting of the Physical Society, November 27, 1909.

to a very perfect mixing of the constituents. On gradually heating this specimen two temperatures (125° and 170°) were found at which very marked increase in induction took place. When annealed from 125° the increase in induction is permanent and is accompanied by a marked decrease in hysteresis. Annealing from 170°, on the contrary, does not leave the specimen in as good a condition as the original as to either maximum induction or hysteresis loss. Annealing from 223° at which temperature it was nearly non-magnetic greatly decreased the induction and the hysteresis losses became relatively enormous. On the contrary quenching from temperatures from 220 to 260 degrees restored the specimen in large measure to its original condition. Other specimens behaved in a similar manner although none of the others seemed as sensitive to heat treatment as no. 1. A curve showing the extent of recovery on chilling from various temperatures indicates a maximum at 243°. After quenching the specimens again showed marked improvement at the same temperatures as before. No such effect occurred after annealing from the neighborhood of 200°. The transformation points were not changed by any of the heat treatments and appeared to depend wholly upon composition as previously found by one of the writers.

While taking the original curves on no. 1, it was noticed that on removal of the magnetizing field, a sharp click was produced, distinctly audible at a distance of ten or fifteen feet. All other specimens were found to give the same result in a degree depending on their magnetic softness. When no. 1 was hardened by annealing, this effect could be observed only by placing the ring to the ear. No sound appears to be produced when the field is applied, wherein it is different from the analogous phenomena in the case of iron.

The microscopic examination previously made by one of us shows that the magnetic quality of these alloys is closely associated with a particular type of crystal which is however itself magnetic only under certain temperature conditions and which probably contains in its structure molecular groups which are the magnetic units. If in addition these crystals contain a matrix of two components one of which softens at 120° and remains soft on annealing while the other softens at 170° but hardens on annealing it seems possible to explain the observed effects as the result of mechanical constraints imposed by the matrix upon the magnetic group.

PHYSICAL LABORATORY,
UNIVERSITY OF UTAH,
November 6, 1909.

Magnetic Properties of Heusler Alloys.[1]

By E. B. Stephenson.

A SERIES of alloys with varied percentage composition was made in the university foundry and tests were made of the magnetic properties by the magnetometric method. These properties varied with the temperature at which they were determined and with the previous heat treatment. It was found that when heated to a particular temperature, about 650° C., and allowed to cool in air, the alloys were almost non-magnetic. By use of a method similar to the Frankenheimer method for the calibration of thermocouples, cooling curves were run, and it was found that a transformation point occurs at about the same temperature, accompanied by an evolution of heat.

The cooling curves were those characteristic of solid solutions.

Photo-micrographs were taken of specimens quenched from various temperatures, and additional data were collected in regard to several physical properties.

The Effect of Temperature on the Magnetic Properties of Electrolytic Iron.[1]

By Earle M. Terry.

THIS paper is a continuation of some work, a preliminary report of which was presented to the Physical Society at the Evanston meeting in November, 1908. As stated there, the purpose was to test Burgess electrolytic iron, which has been shown to be very pure, at temperatures ranging from that of liquid air up to the magnetic transformation point, with a view to determining to what extent the facts already discovered are characteristic of iron itself and what are the effects of impurities.

The following are the principal characteristics of electrolytic iron which have been established by this investigation:

1. Freshly prepared iron is very hard magnetically.

2. Different samples show marked dissimilarities at low fields which disappear upon heating to 1000° C.

3. At high fields, all samples are quite similar, the values obtained for susceptibility being intermediate between those of Leich and Schild.

4. Plunging into liquid air produces no permanent hardening.

5. The retentivity has a maximum in the neighborhood of room temperature.

[1] Abstract of a paper presented at the Urbana meeting of the Physical Society, November 27, 1909.

6. Marked softening magnetically occurs at the hydrogen transformation points (300° C. and 500° C.) as shown by depressions in the curves for the variation of hysteresis loss per cycle and field for maximum permeability with temperature. These depressions disappear after annealing.

7. Ferro-magnetism reappears on cooling at the same temperature at which it disappears on heating. This temperature is 785° C.

8. The depression in the permeability-temperature curves obtained by Morris for Swedish iron does not exist for electrolytic iron.

9. The best temperature for annealing is 1100° C.

10. Although when properly annealed it has a lower coercive force and a higher maximum permeability than Swedish iron, its high retentivity causes a larger hysteresis loss.

AN APPARATUS FOR MEASURING SOUND.[1]

BY F. R. WATSON.

THE apparatus was designed to be used in an investigation of the acoustics of an auditorium, and for that reason it was found desirable to have an instrument that was portable and easily adjusted. A suitable apparatus was set up consisting of a telephone receiver connected to a Duddell thermogalvanometer.

To augment feeble sounds, the principle of resonance was used. Thus the source of sound was adjusted to give a maximum effect with the telephone plate used. Further augmentation of the effect was secured by placing a resonator of suitable dimensions over the telephone plate, by inserting a condenser in the circuit and by adjusting the distance between the telephone plate and the magnet.

By means of this apparatus maxima and minima of sound were easily detected in a small laboratory, and a series of standing waves near a wall measured. The apparatus is not merely a detector of sound, but gives quantitative measurements that may be repeated.

POLARIZATION OF CADMIUM CELLS.[1]

BY R. R. RAMSEY.

CELLS of the H form were polarized by short-circuiting or by connecting them to an outside E.M.F. until their voltage was very small, 0.1 volt say. By means of a siphon filled with cadmium sulphate solution connection was made to unpolarized cells and it was found that the E.M.F. between the cadmium amalgam terminal of the polarized and the mercury terminal of the unpolarized cell was practically normal

[1] Abstract of a paper presented at the Urbana meeting of the Physical Society, November 27, 1909.

while the E.M.F. between the cadmium amalgam terminal of the unpolarized cell and the mercury terminal of the polarized cell was the same as the E.M.F. of the polarized cell.

A cell was short-circuited for some days and part of the mercury was removed with a pipette washed, filtered through a pin hole, and made the mercury terminal of new cell from which the mercurous sulphate was omitted. The E.M.F. of this cell was small and after standing seven months is less than 0.1 volt. The original cell has recovered to practically the normal value.

On the Mechanical Equivalent of Heat by a Porous Plug Method.[1]

By J. R. Roebuck.

A NEW determination of the mechanical equivalent of heat is being carried out by forcing water through a porous plug and reading the drop in pressure and the resulting difference in temperature. To this must be added the temperature drop on free expansion between these pressure limits. This will then give the equivalent in terms of the heat capacity of water and the weight of a mercury column.

The porous plug is of an entirely new form devised by Burnett and Roebuck and described by them in detail in a paper now in course of publication in The Physical Review. A porous porcelain cylinder with one hemispherical end is surrounded outside by the fluid under the higher pressure. The fluid passes through the wall and escapes from the open end. A platinum thermometer is placed with its bulb entirely surrounded by the porous wall and the stem surrounded by the escaping fluid. Under these conditions heat flow outward is entirely eliminated by the liquid flow inward and the only radiation and conduction errors are those from the support of the porous plug. These will affect the fluid almost entirely after it has passed the thermometer. The initial temperature is read by a second thermometer placed in the flowing liquid just before entering the plug. The temperature of the entering fluid is fixed by passage through a long coiled copper tube which with the plug carrying tube is immersed in a large electrically heated thermostat provided with specially delicate regulation.

The water under pressure is supplied by a special six plunger pump and the maximum pressure contemplated is 100 atmos. The pressure is regulated by a rotating piston which, by its rise or fall, introduces or cuts out resistance from the armature circuit of the motor driving the pump. For the final pressure reading an open U tube mercury manom-

[1] Abstract of a paper presented at the Urbana meeting of the Physical Society, November 27, 1909.

eter after the Kamerlingh Onnes pattern was constructed. This is a series of glass U tubes partly filled with mercury and the pressure is transmitted from one lower mercury surface to the next upper by means of compressed air. The eight tubes will read about 35 atmos. pressure differences.

The apparatus is all assembled and tested and preliminary readings are in progress.

PHYSICS DEPARTMENT,
UNIVERSITY OF WISCONSIN.

A METHOD OF DETERMINING THE OPTICAL CONSTANTS OF METALS APPLICABLE TO MEASUREMENTS IN THE INFRA-RED SPECTRUM.[1]

BY L. R. INGERSOLL.

THE ordinary way of determining the refractive index and absorption index of metals is to find the incidence for which circularly polarized light is reduced to plane polarized as well as the azimuth of polarization of the latter. In the present method the process is reversed by determining the angle of incidence and plane of polarization — principal incidence and principal azimuth respectively — for which plane polarized light is reduced to circular. The circularly polarized light is recognized as such by allowing it to pass through a large Wollaston double image prism. Two "sections" at right angles to each other are thus taken of the beam and when these are equal, for all azimuths of the Wollaston, the polarization of the beam must be circular.

The instrumental arrangement is very similar to that already used by the writer in work on magnetic rotation.[2] The two beams from the Wollaston are analyzed with the aid of a sensitive spectrobolometric apparatus and equality of intensity is very accurately determined. The principal azimuths and incidences and hence the optical constants may be determined in this way for a range of spectrum from the D lines to $\lambda = 2.2\,\mu$ with an accuracy at least equal to that of the best visual measurements.

Preliminary measurements have been made on steel, nickel, and cobalt. These show refractive indices at wave-length $2\,\mu$, nearly twice as large as for the D lines and do not indicate any considerable increase after this wave-length. Reflecting powers computed from these optical constants are in excellent agreement with the measurements of Hagen and Rubens, especially for the longer wave-lengths.

[1] Abstract of a paper presented at the Urbana meeting of the Physical Society, November 27, 1909.

[2] See PHYS. REV., Dec., 1906, and Phil. Mag., Jan., 1906, and July, 1909.

The Absolute Value of the Moments of Elementary Magnets.[1]

By Jakob Kunz.

THE moments of the molecular magnets play a fundamental rôle in the theory of magnetism. The electron theory of ferromagnetism due to Professor P. Weiss allowsthe determination of the moments of the elementary magnets of iron, nickel and magnetite. It appears that the molecular magnet of iron contains two atoms, that of nickel six, while each molecule Fe_3O_4 of magnetite constitutes an elementary magnet. From the moments of the molecular magnets the number of atoms of hydrogen per unit volume can be derived, and the value thus determined coincides with that deduced from radioactive phenomena by Rutherford.

"The Value of e by Wilson's Method."[1]

By L. Begeman.

THE article contains three sets of data. The first set contains data of observations taken on clouds composed of singly charged droplets. The second set contains data of observations on layers in the clouds composed of doubly charged droplets and the third set deals with multiply charged droplets.

There are 28 separate determinations of single charges made with fields of different intensity. The average of all the determinations of the first set is 4.67×10^{-10} E.S. units for the charge of e; the second set 4.69×10^{-10} E.S. units and the third 4.65×10^{-10}.

The article contains also data to show that the errors due to evaporation in the clouds are within the limits of other experimental errors.

The Absorption of X-Rays an Additive Property.[1]

By R. A. Millikan and E. J. Moore.

THE object of this investigation was to make a careful test of the recently widely circulated assertion[2] that a body becomes more transparent to the X-ray from a given source when it is simultaneously traversed by a transverse X-ray beam from a second source.

The observations presented in this paper show conclusively that the ionizing effects which an X-ray beam can produce after passing through

[1] Abstract of a paper presented at the Urbana meeting of the Physical Society, November 27, 1909. The paper is published in full in the Journal of the American Medical Association, Vol. LIII., p. 1026, September 25, 1909.

[2] A New Method of Taking X-Ray Pictures, Jour. Am. Med. Assn., April 17, 1909, LII., p. 1246.

an absorbing body are altogether independent of whether or not the body is being simultaneously traversed by other X-ray beams.

THE ELASTIC BEHAVIOR OF PLATINUM-IRIDIUM WIRE.[1]

BY K. E. GUTHE AND L. P. SIEG.

THE elastic behavior of platinum-iridium wires was studied by the method of torsional vibrations. The vibrating system was set swinging with large amplitudes and allowed to die down. Amplitudes and periods were observed and the conditions of the experiments varied in several ways. The following is the summary of the results.

1. Platinum-iridium wires containing over 30 per cent. iridium show striking peculiarities in their elastic behavior which become the more marked the higher the percentage of iridium.

2. For small amplitudes the period of torsional vibration is nearly proportional to the amplitude; but for larger amplitudes the rate of increase of the period becomes smaller and for very large amplitudes the periods tend towards a constant value.

3. The logarithmic decrement increases with the amplitude, reaches a maximum, after which it decreases again and probably reaches a minimum for very large amplitudes. The maximum is the more pronounced the larger the original distortion.

4. If the wire has been allowed to rest some time before the torsional vibrations are produced the total number of vibrations necessary to bring the system to rest is the smaller the larger the initial amplitude.

5. When tested by the static method the wires closely obey Hooke's law. The torsional moment calculated from the static experiment is larger than the largest torsional moment found by the dynamic method.

[1] Abstract of a paper presented at the Urbana meeting of the Physical Society, November 27, 1909.